Recoil and Kinematics in Parton Showers

Emma Simpson Dore[1]

Current work and future plans | August 20, 2020

[1] In collaboration with Simon Plätzer, Max Löschner and Stefan Gieseke

Parton Showers

- Bridge between hard matrix element and non-perturbative physics
- Facilitates resummation of leading logarithmic contributions
- Uses **emission kernels** to describe rate of emission for a propagating quark/gluon to emit an additional quark/gluon
- Contains **mapping** to factorise emissions within the phase space

$$d\sigma = d\sigma_{hard}(Q) \times PS(Q \to \mu) \times Had(\mu \to \Lambda) \times ...$$

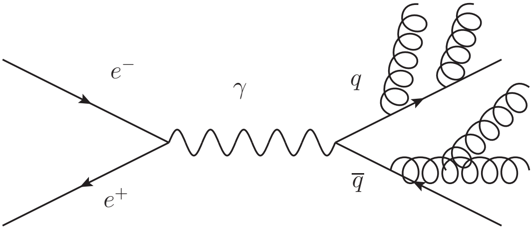


Diagram of an e^+e^- collision and possible parton shower

The future of parton showers

Push to higher orders and improved accuracy :

- Beyond 1$\rightarrow$ 2 branching in kinematics and splitting kernels
- Global vs. local recoil schemes
- Include more spin and colour interferences

Will be central to address[2]:

- Singularity structure for NNLO matching, increasingly important
- Lack of systematic expansion of uncertainties at higher orders
- Ad hoc prescriptions for azimuthal correlations
- Improve simulation for non-global observables

[2] Dasgupta et al. 2018; Bewick et al. 2019.

Building a parton shower

- Key components:
  - Kinematic mapping
  - Emission kernels/splitting functions
  - Choice of evolution variable and recoil scheme

Current implementation in Herwig (dipole shower):

$$\begin{aligned} \textit{Emitter} \rightarrow \ q_i &= z p_i + y(1-z) p_r + k t \ , \\ \textit{Emission} \rightarrow \ k_1 &= (1-z) p_i + z y p_r - k t \ , \\ \textit{Spectator} \rightarrow \ q_r &= (1-y) p_r \ , \end{aligned}$$

- Develop a new mapping in order to:
  - Distribute recoils globally
  - Factorise without explicitly taking soft or collinear limits

Mapping for single emission with global recoil

Mapping with soft and collinear parameters:

$$q_i = \frac{1}{\hat{\alpha}}\Lambda\left[(1-\alpha_{i1})p_i + (y_i - (1-\alpha_{i1})\beta_{i1})n_i - \sqrt{1-\alpha_{i1}}\sqrt{\alpha_{i1}\beta_{i1}}\,n^{(i)}_{\perp,1}\right] ,$$
$$k_{i1} = \frac{1}{\hat{\alpha}}\Lambda\left[\alpha_{i1}p_i + (1-\alpha_{i1})\beta_{i1}n_i + \sqrt{1-\alpha_{i1}}\sqrt{\alpha_{i1}\beta_{i1}}\,n^{(i)}_{\perp,1}\right] ,$$
$$q_r = \frac{1}{\hat{\alpha}}\Lambda p_r , \qquad (r = (1,..,n), \quad r \neq i)$$

- Above case is single emitter q_i with one emission k_{i1}, in this case $\alpha_{i1} \to (1-z)$ and $y_i = \beta_{i1}$
- Includes soft limit ($\alpha_1, y_i, \beta_{i1} \to 0$) and collinear limit ($y_i, \beta_{i1} \to 0$)
- $n_\perp$ represents the transverse component (kt)
- Includes global treatment of recoil via Lorentz transformation, Λ

Action of Lorentz transformation

- Momentum conservation requires: $q_i + k_{i1} + q_r = p_i + p_r = Q$
- Use Lorentz transformation(LT) to distribute recoil
- n-vector gives backwards direction $n_i = Q - \frac{Q^2}{2p_i \cdot Q} p_i$

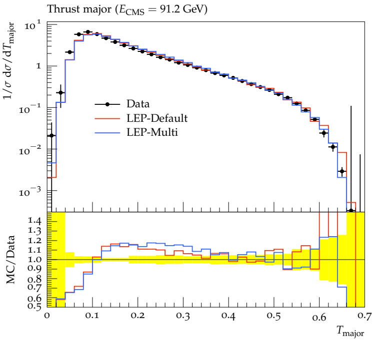
Can be expressed as:

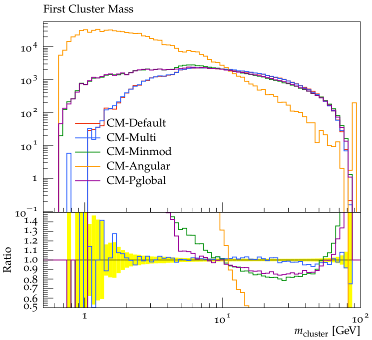
$$\Lambda^{\mu}{}_{\nu} \left[Q^{\nu} + N^{\nu} \right] = \hat{\alpha} Q^{\mu} , \qquad N = \sum_{i \in \mathbf{S}} y_i n_i$$

- For single emitter $\hat{\alpha} = \sqrt{1 + y_i}$, in collinear limit $\hat{\alpha} \to 1$
- In collinear limit Λ acts as metric

Herwig Implementation

- Mapping inc. transform implemented in Dipole Shower, (Multi)
- ALEPH analysis[3], parton level and cluster mass analyses
- Comparison of different mappings including PanGlobal[4]





Plot of thrust major and first cluster mass for 100,000 events (Preliminary plots)

[3] Heister 2004.

[4] Dasgupta et al. 2020.

Mapping for two emissions

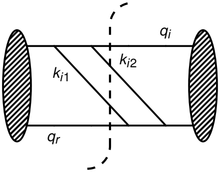
Two emissions, one emitter:

$$q_i = \frac{1}{\hat{\alpha}}\Lambda\Big[\,(1-\alpha_{i1}-\alpha_{i2})\,p_i + (y_i - (1-\alpha_{i1}-\alpha_{i2})(\beta_{i1}+\beta_{i2}))\,n_i - \sqrt{(1-\alpha_{i1}-\alpha_{i2})}\left(\sqrt{\alpha_{i1}\beta_{i1}}n^{(i)}_{\perp,1} + \sqrt{\alpha_{i2}\beta_{i2}}n^{(i)}_{\perp,2}\right)\Big]$$

$$k_{i1} = \frac{1}{\hat{\alpha}}\Lambda\left[\alpha_{i1}p_i + (1-\alpha_{i1}-\alpha_{i2})\beta_{i1}\;n_i + \sqrt{(1-\alpha_{i1}-\alpha_{i2})}\sqrt{\alpha_{i1}\beta_{i1}}n^{(i)}_{\perp,1}\right]$$

$$k_{i2} = \frac{1}{\hat{\alpha}}\Lambda\left[\alpha_{i2}p_i + (1-\alpha_{i1}-\alpha_{i2})\beta_{i2}\;n_i + \sqrt{(1-\alpha_{i1}-\alpha_{i2})}\sqrt{\alpha_{i2}\beta_{i2}}n^{(i)}_{\perp,2}\right]$$

$$q_r = \frac{1}{\hat{\alpha}}\Lambda p_r\;, \qquad (r = 1,..,n \qquad r \neq i)$$



Examples of two emission case

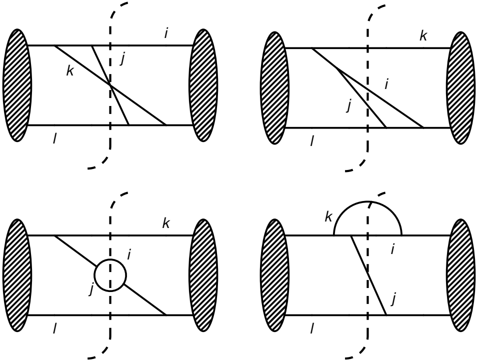
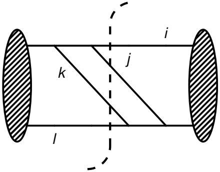


Figure: Examples of 2 emission diagrams.

- Complicated interaction of soft and collinear singularities for two emissions
- Devise framework to separate singularities and collect into kernels

Example: Separating singularities

$$A^{(1)}_{ijkl} =$$ 

Singularities in the above diagram:

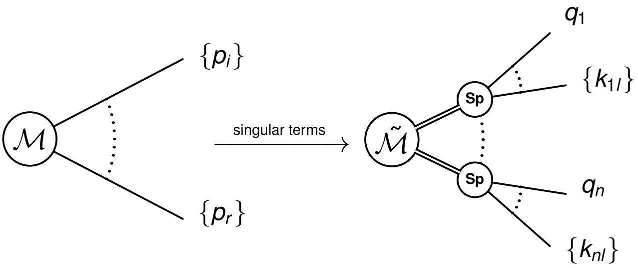
$$\frac{1}{S_{ijk}}\frac{1}{S_{ij}}\frac{1}{S_{kl}}\frac{1}{S_{jkl}} \times \frac{m(S_{kl}S_{jkl} + S_{ij}S_{ijk} + S_{ijk}S_{jkl}) + (S_{kl} + S_{ij})S_{ijk}S_{jkl}}{m(S_{kl}S_{jkl} + S_{ij}S_{ijk} + S_{ijk}S_{jkl}) + (S_{kl} + S_{ij})S_{ijk}S_{jkl}}$$

- Where $S_{ijk} = S_{ij} + S_{ik} + S_{jk}$ and $S_{ij} = (q_i + q_j)^2$
- Three different triple collinear cases, (ijk), (jkl) and (ij, kl)
- Sub-leading contributions to (ijl) and (ikl)
- Aim to partition singularities so can be expressed as a sum

Overview

Tools:

- New mapping which exposes soft and collinear singularities for up to n-emissions
- Mapping treats recoil globally via Lorentz Transformation
- Comprehensive framework for organising the singularities for to 2-emission case and beyond
- Partitioning algorithm including all triple collinear limits and beyond



Summary and WIP

Current checks/tests:

- Can reproduce collinear splitting functions for one and two emissions
- Phase space factorisation for general mapping determined
- Can reproduce known triple collinear, double soft and soft-collinear functions[5]

Work in progress:

- Implementation of mapping in Herwig with correct phase space
- Two emission splitting functions and mapping in code
- NNLO subtraction, combine real and virtual contributions differentially

[5] Catani and Grazzini 2000.

Past and Future Directions

Experience before PhD:

- Motivated by interest from working with MC generated data
- Firstly from ATLAS project working with W/Z decays
- Masters project also used MC generators for future collider predictions

Future directions:

- Data-driven discovery, look to the data for signs of new physics
- HL-LHC, computational challenges, large data volumes
- Application of experience working with event generators
- More in-depth use of analysis tools

Past and Future Directions

Interest in this position:

- Top-quark pair production, new physics posibilities
- Simplified models, DM searches, scalar/pseudoscalar mediators
- CMS collaboration involvement
- DESY, Uni Hamburg collaboration

References I

- Gavin Bewick et al. “Logarithmic Accuracy of Angular-Ordered Parton Showers”. In: (2019). arXiv: 1904.11866 [hep-ph].
- S. Catani and M. H. Seymour. “A General algorithm for calculating jet cross-sections in NLO QCD”. In: *Nucl. Phys.* B485 (1997). [Erratum: Nucl. Phys.B510,503(1998)], pp. 291–419. DOI: 10.1016/S0550-3213(96)00589-5,10.1016/S0550-3213(98)81022-5. arXiv: hep-ph/9605323 [hep-ph].
- Stefano Catani and Massimiliano Grazzini. “Infrared factorization of tree level QCD amplitudes at the next-to-next-to-leading order and beyond”. In: *Nucl. Phys.* B570 (2000), pp. 287–325. DOI: 10.1016/S0550-3213(99)00778-6. arXiv: hep-ph/9908523 [hep-ph].
- Mrinal Dasgupta et al. “Logarithmic accuracy of parton showers: a fixed-order study”. In: (2018). arXiv: 1805.09327 [hep-ph].

References II

- Mrinal Dasgupta et al. “Parton showers beyond leading logarithmic accuracy”. In: *Phys. Rev. Lett.* 125.5 (2020), p. 052002. DOI: 10.1103/PhysRevLett.125.052002. arXiv: 2002.11114 [hep-ph].
- A. Heister et al. “Studies of QCD at e+ e- centre-of-mass energies between 91-GeV and 209-GeV”. In: *Eur. Phys. J.* C35 (2004), pp. 457–486. DOI: 10.1140/epjc/s2004-01891-4.

- QCD and Collider Physics, Ellis, Stirling and Webber. (p.170)