Lund plane for parton shower development

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Outline

• Intro & Lund diagrams for showers

• Shower issues: Lund plane as diagnostic tool

• Logarithmic accuracy of showers: problems in dipole showers

• Shower accuracy criteria: Lund plane formulation

• Designing accurate showers: Lund plane as a guide and Lund based observables for tests.

• Outlook
Intro : Parton showers

Elements of GPMC for LHC

1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event

• **Core component of all GPMCs** used in virtually all high energy collider analyses.

• Beyond hard process **the only component directly connected to SM (QCD) Lagrangian**. Holds the key to precision in MC approach.
Showers and multiple scales

- Showers describe evolution from TeV scale of hard process down to ~ 1 GeV.

\[ \frac{dP(S_n, v)}{d \ln 1/v} = -f(S_n, v)P(S_n, v) \]

- Considerable freedom in design e.g. choice of evol. variable \( v \) and kernel \( f \). But also constraints from soft/collinear limits of QCD.

- Many observables **sensitive to multiple disparate scales**. Need resummation offered by shower.

Any LHC process involves large scale hierarchy
Angular ordered and dipole showers

Angular ordered parton shower (HERWIG) : starting point is collinear limit and fixes soft limit accounting for coherence. Sequence of 1 to 2 parton splittings.

Dipole showers start from soft limit. Sequence of 2 to 3 soft splittings. (e.g. Pythia 8, Dire, PanScales, Alaric…)

Comes with questions: how to assign recoil?

Also formulated in large Nc limit for simplicity. Often partially corrected by using right colour factors e.g. $C_F$ for emission off quark leg.
Dipole showers and Lund diagrams

\[ d\sigma \approx \sigma_0 \frac{C_A}{2} \frac{\alpha_s(p^2)}{2\pi} d\ln p^2 d\eta \]

Note use of \( C_A/2 \) colour factor. Large \( N_c \) limit

Uniform distribution of soft emissions in Lund variables

Emissions are ordered in suitable evolution variable \( \mathcal{U} \)

\[ |\eta| < \frac{1}{2} \ln \frac{s}{p^2} \]

Allowed phase space is triangular region

Represented by Lund “Origami” diagrams

Andersson, Gustafson, Lonnblad, Petterssen 1989
Dipole emissions on Lund diagrams

\[ \Delta \eta = \ln \frac{s_{qq}}{k_{\perp 2}^{2}} + \ln \frac{s_{g1\bar{q}}}{k_{\perp 2}^{2}} = \ln \frac{s}{k_{\perp 2}^{2}} + \ln \frac{k_{\perp 1}^{2}}{k_{\perp 2}^{2}} \]

Phase space for emissions increases with each subsequent emission.

Andersson, Gustafson, Nilsson, Sjorgen 1990
• Differences between shower predictions are important limiting factor in phenomenology.
• Lund plane measurements valuable for systematically probing physical origin
• Differences natural given freedom in shower design. But once we fix shower accuracy they should be subleading effects.
• But how to tell if the differences are a worry? Spread between showers often taken as measure of uncertainty.
A common framework: logarithmic accuracy

Showers give a perturbative approximation to an observable. Resum large logs for multi-scale observables to all orders (pure fixed-order breaks down)

\[
\Sigma(Q, vQ) = \sum_{n,m \leq 2n} c_{nm} \alpha_s^n L^m \quad v \ll 1 \quad L = \ln \frac{1}{v}
\]

\[
\Sigma(Q, vQ) \sim \exp[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \cdots]
\]

- \(g_1\) is leading log (LL). Controls all double log (\(m=2n\)) terms in expansion.
- Including \(g_2\) gives NLL and \(g_3\) is NNLL.
- NLL is a must for accurate pheno.

Multiscale observable with exponentiation. Accuracy depends on \(g_n\)

Catani, Turnock, Trentadue and Webber 1992
**Dipole shower problems**

Shower accuracy proved notoriously difficult to quantify. Believed for long to be somewhere between naïve LL and full NLL

- Relatively recent developments for common dipole showers (incl. Pythia) revealed substantial issues

  - Issues found for emissions that are well separated in LP Leading and next to leading log trouble!

MD, Dreyer, Hamilton, Monni, Salam  2017
Recoil problem

- Dipole emission split into two “halves” with one leg acting as emitter with other as spectator.
- The crossover happens at $\eta = 0$ in dipole rest frame.
- Transverse recoil taken by emitter.

Bad choice beyond 1st emission!

MD, Dreyer, Hamilton, Monni, Salam 2017

$dP_2 = \frac{C_F^2}{2!} \prod_{i=1,2} \left( \frac{2\alpha_s(p_{\perp,i}^2)}{\pi} \frac{dp_{\perp,i}}{p_{\perp,i}} \frac{d\eta_i}{2\pi} \right)$

- Breaking of simple QCD indep. emission result
- Failure at NLL for several common observables e.g. event shapes
Colour problem

Double strong ordered config: \( p_{\perp,2} \ll p_{\perp,1} \quad \eta_2 \gg \eta_1 \)

- \( p_1 \): Emits with weight \( \propto C_A/2 \)
- \( p_2 \): Emits with weight \( \propto C_F \)

Transition from \( C_A/2 \) to \( C_F \) in wrong place! Radiation collinear to quark has \( C_A/2 \) component.

Incorrect LL (double logarithms, subleading colour) for observables like thrust.

MD, Dreyer, Hamilton, Monni, Salam 2017
Lund Plane criteria for shower accuracy

- **LL accuracy**: shower ME → QCD ME
  - in limit where every pair of emissions is well separated in both LP variables

- **NLL accuracy**: shower ME → QCD ME
  - in limit where every pair of emissions is well separated in at least one of LP variables

Plus correctness of virtual corrections to soft/collinear emissions

MD, Dreyer, Hamilton, Monni, Salam, Soyez, 2020
PanScales collaboration

Oxford
- Melissa van Beekveld
- Jack Helliwell
- Rok Medves
- Frederic Dreyer
- Gavin Salam
- Ludo Scyboz

CERN
- Mrinal Dasgupta
- Gregory Soyez
- Pier Monni
- Alexander Karlberg
- Alba Soto Ontoso
- Silvia Ferrario Ravasio

PanScales
A project to bring logarithmic understanding and accuracy to parton showers
NLL showers step 1: leading Nc

PanScales dipole showers give 2 solutions to recoil issue:

- Panlocal: dipole local recoil but emitter-spectator cross-over at equal angles in event c.o.m. frame
- PanGlobal: a global recoil scheme with a rescaling and boost

A general form for ordering variable

\[ v \sim k_t e^{-\beta |\eta|} \]

Followed up by other groups: Forshaw et al. 2020, Herren et al. 2022

e+e- showers: MD, Dreyer, Hamilton, Monni, Salam, Soyez 2020

Lund observable for NLL recoil effect

- Examine azimuthal angle between hardest emissions in primary Lund declustering of jet.

- Observable directly probes whether shower gets independent emission structure of matrix element uniform dist.

\[ \Delta \psi_{12} \]

Single strong ordered config: \( p_{\perp,2} \sim p_{\perp,1} \eta_2 \gg \eta_1 \)

\[ k_2 \] takes transverse recoil from \( k_2 \) although \( k_2 \) collinear to quark.

\[ p_{\perp,1} \rightarrow p_{\perp,1} - p_{\perp,2} \]

\[ dP_2 = \frac{C_F}{2!} \prod_{i=1,2} \left( \frac{2\alpha_s(p_{\perp,i}^2)}{\pi} \frac{dp_{\perp,i}}{p_{\perp,i}} \frac{d\eta_i}{2\pi} \right) \]

MD, Dreyer, Hamilton, Monni, Salam, Soyez 2020
Lund observable for NLL recoil

- Incorrect showers show a dependence on $\Delta \psi$
- There is an in principle significant effect

Measuring variables like this important for comparison of NLL versus NLL incorrect dipole showers

MD, Dreyer, Hamilton, Monni, Salam, Soyez 2020
NLL showers step 2: colour and the Lund picture

• One sol. directly based on QCD coherence (Lund plane picture.)

• gg dipoles can radiate with $C_F$ colour factor. Realised decades ago in old Lund papers. Not implemented in modern dipole showers till this work.

• Gives full colour LL and for a set of key (global) observables full colour NLL.
NLL (full colour) for global observables

Hamilton, Medves, Salam, Scyboz, Soyez, 2020
NLL showers step 3: spin and Lund observables

Azimuthal correlation defined using highest kt declustering in primary and secondary Lund planes

Karlberg, Salam, Scyboz, Verheyen, 2021

- General NLL accuracy needs incl. of spin correlations.
- Implemented in PanScales by adapting Collins-Knowles algorithm for dipole showers
- New Lund de-clustering observable developed for testing.
Summary and outlook

- Lund diagrams have long been a part of how we think about dipole showers. More recently LJP measurements proposed and carried out. Offers clean way of separating physical effects of different origin.

- Dipole shower accuracy major step forwards: NLL showers are here. LJP has been crucial in construction of PanScales set of showers.
  
  New PanScales DIS shower: van Beekveld and Ferrario Ravasio 2023

- LJP measurements and observables crucial to probing NLL showers and differences with current widely used showers e.g. Pythia.

- Can look forward to NNLL showers. Here we will need correct ME when pair of emissions are close in LJP Higher order splitting kernels.

- Expect new LJP observables to emerge during development and testing of future NNLL showers. (see talk by A. Soto-Ontoso at this meeting)