Lund plane for parton shower development

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First Lund jet plane institute
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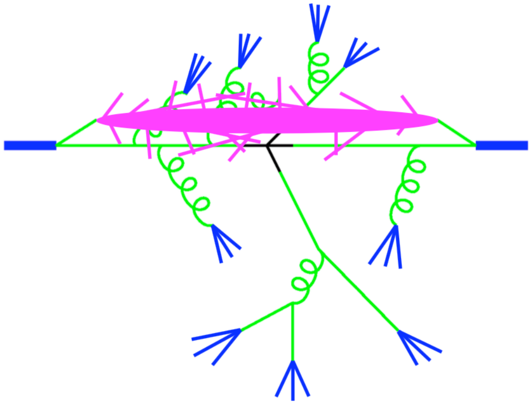
Outline

- 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

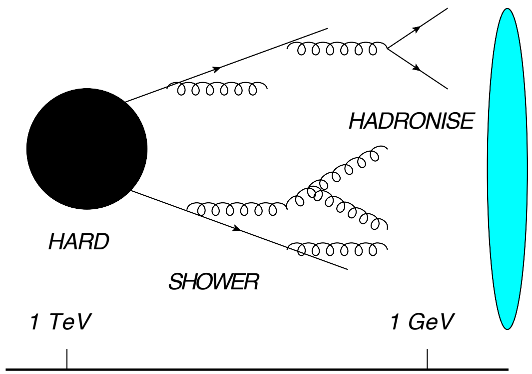
Elements of GPMC for LHC

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



Any LHC process involves large scale hierarchy

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

$$\frac{dP(\mathcal{S}_n, v)}{d\ln 1/v} = -f(\mathcal{S}_n, v)P(\mathcal{S}_n, v)$$

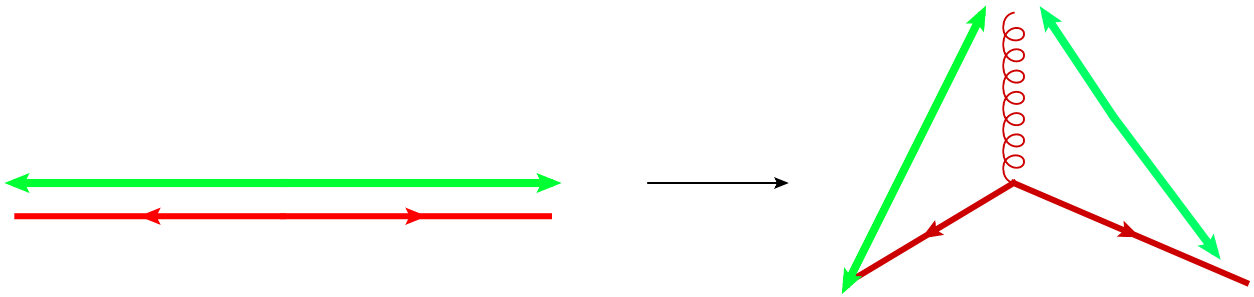
Considerable freedom in design e.g. choice of evol. variable v and kernel f. But also constraints from soft/collinear limits of QCD.

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

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?**

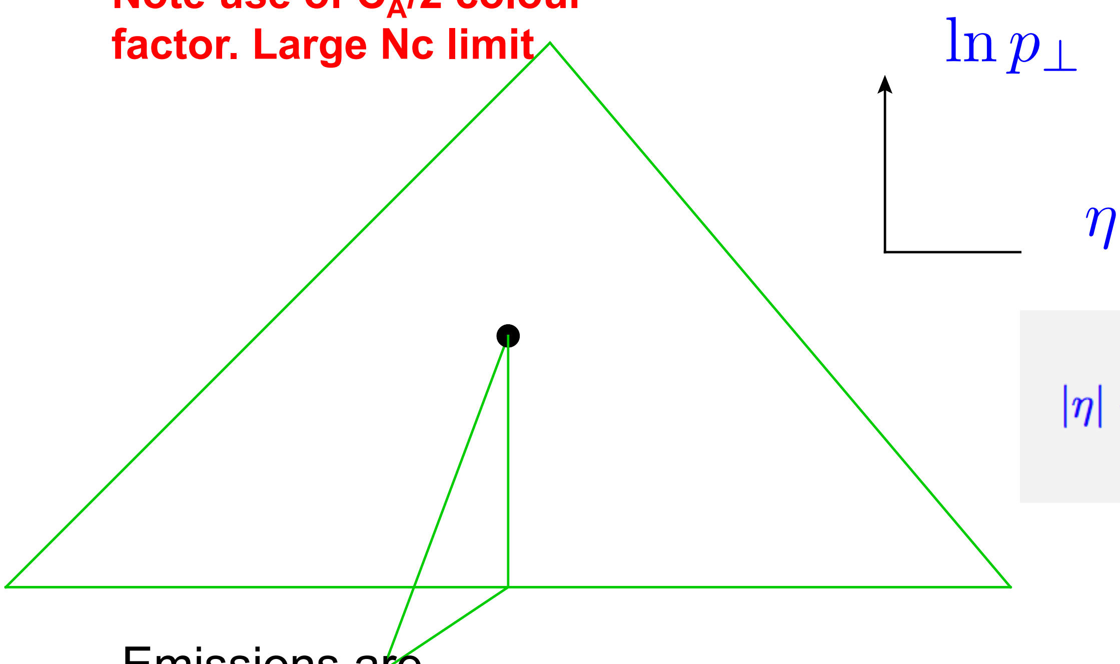
Also formulated in **large Nc limit** for simplicity. Often partially corrected by using right colour factors e.g. C_F for emission off quark leg.

Dipole showers and Lund diagrams

$$d\sigma \approx \sigma_0 \frac{C_A}{2} \frac{\alpha_s(p_\perp^2)}{2\pi} d\ln p_\perp^2 \, d\eta$$

Uniform distribution of soft emissions in Lund variables

Note use of $C_A/2$ colour factor. Large Nc limit



Emissions are **ordered in suitable evolution variable** v

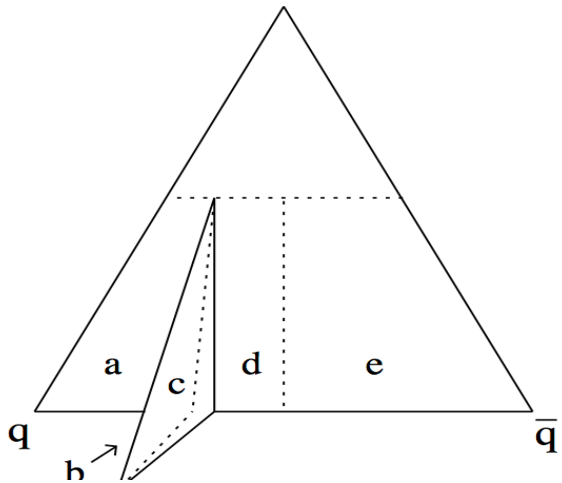
$$|\eta| < \frac{1}{2} \ln \frac{s}{p_\perp^2}$$

Allowed phase space is triangular region

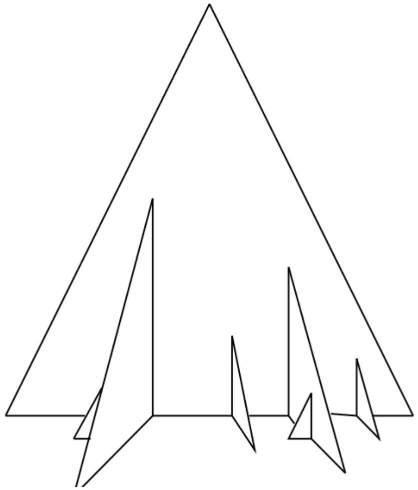
Represented by Lund “Origami” diagrams

Andersson, Gustafson, Lonnblad, Petterssen 1989

Dipole emissions on Lund diagrams



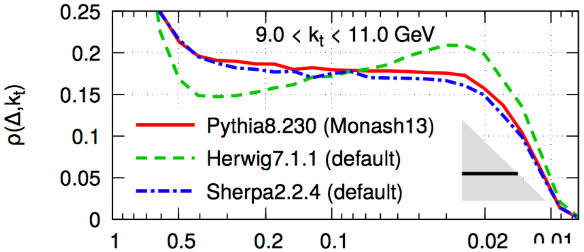
$$\Delta\eta = \ln\frac{s_{qg1}}{k_{\perp 2}^2} + \ln\frac{s_{g1\bar{q}}}{k_{\perp 2}^2} = \ln\frac{s}{k_{\perp 2}^2} + \ln\frac{k_{\perp 1}^2}{k_{\perp 2}^2}$$

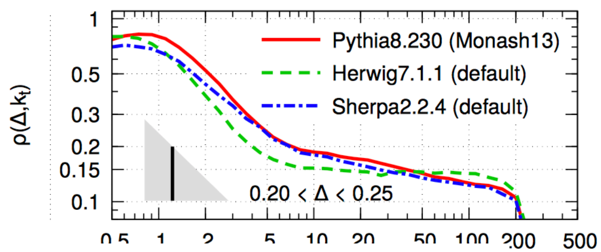


Phase space for emissions increases with each subsequent emission.

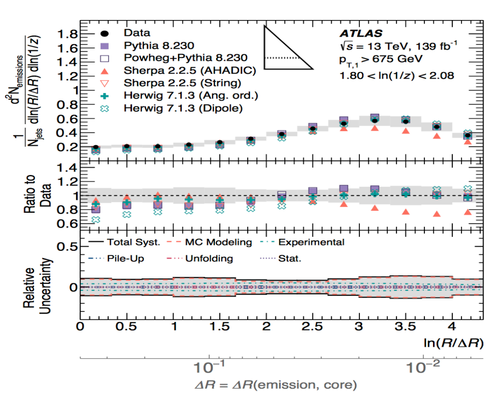
Andersson, Gustafson, Nilsson, Sjorgen 1990

Showers in Lund Plane

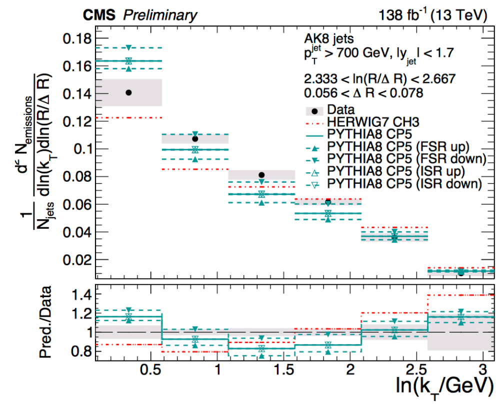




Dreyer, Salam, Soyez 2018



ATLAS Collaboration 2019



CMS collaboration 2023

- 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)

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

Multiscale observable. **Accuracy specified by n and m.**

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

- 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**

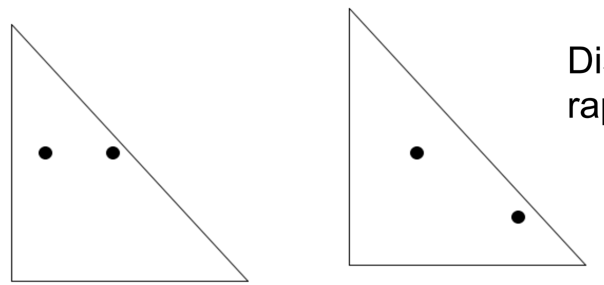
Catani, Turnock, Trentadue and Webber 1992

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

Commensurate k_t disparate rapidity. NLL config.

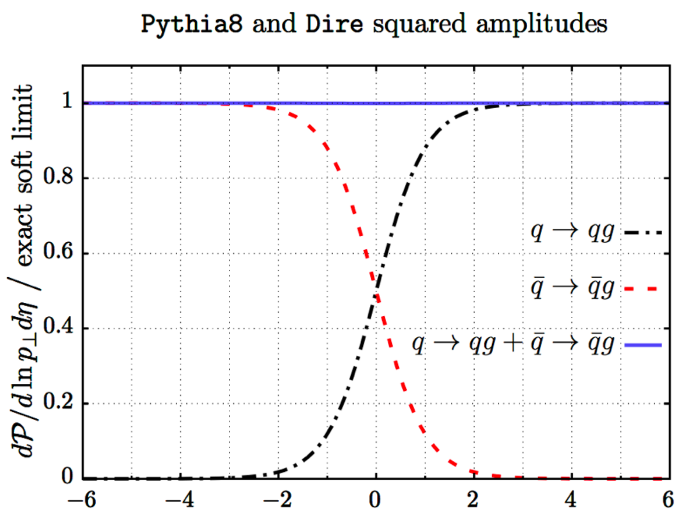


Disparate k_t and rapidity. LL config.

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

MD, Dreyer, Hamilton, Monni, Salam 2017

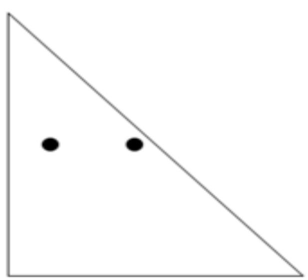
Recoil problem



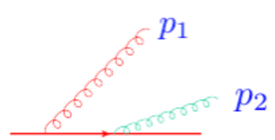
- Dipole emission split into two "halves" with one leg acting as emitter with other as spectator.
- **The crossover happens at $\eta = 0$ in dipole rest frame.**
- **Transverse recoil taken by emitter.**

Bad choice beyond 1st emission !

MD, Dreyer, Hamilton, Monni, Salam 2017



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



k_1 takes transverse recoil from k_2 although k_2 collinear to quark.

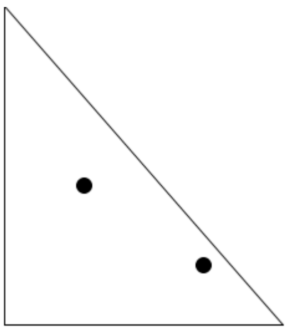
$\mathbf{p}_{\perp,1} \to \mathbf{p}_{\perp,1} - \mathbf{p}_{\perp,2}$

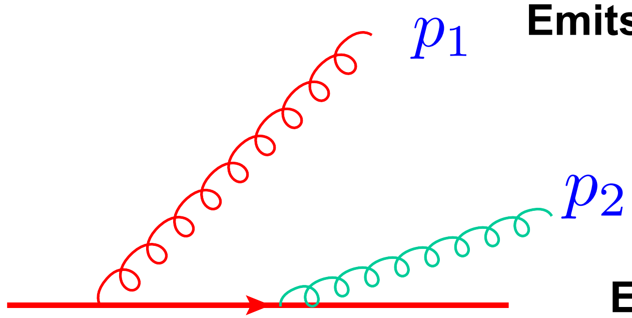
$$dP_2 = \frac{C_F^2}{2!} \prod_{i=1,2} \left(\frac{2\alpha_s(p_{\perp,i}^2)}{\pi} \frac{dp_{\perp,i}}{p_{\perp,i}} d\eta_i \frac{d\phi_i}{2\pi} \right)$$

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

Colour problem

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



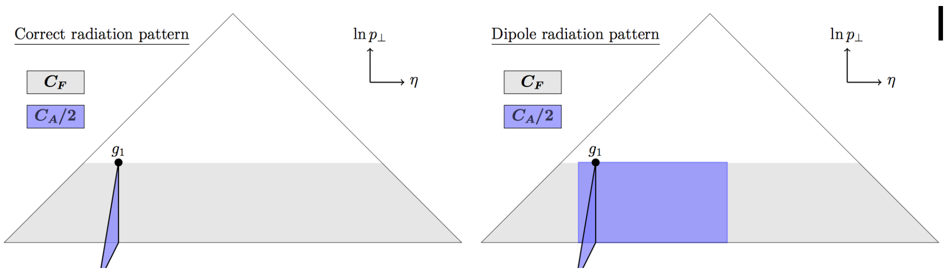


Emits with weight $\propto C_A/2$

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

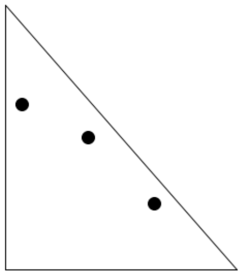


MD, Dreyer, Hamilton, Monni, Salam 2017

Lund Plane criteria for shower accuracy

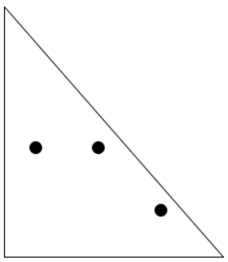
- LL accuracy : shower ME → QCD ME

  in limit where every pair of emissions is well separated in both LP variables



- NLL accuracy : shower ME → QCD ME

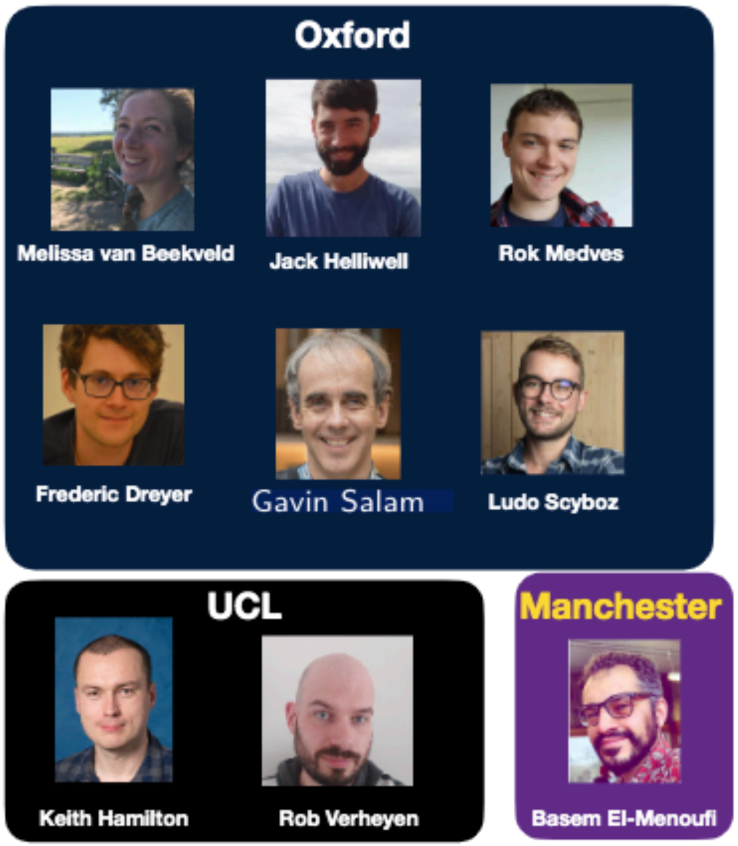
  in limit where every pair of emissions is well separated in at least one of LP variables

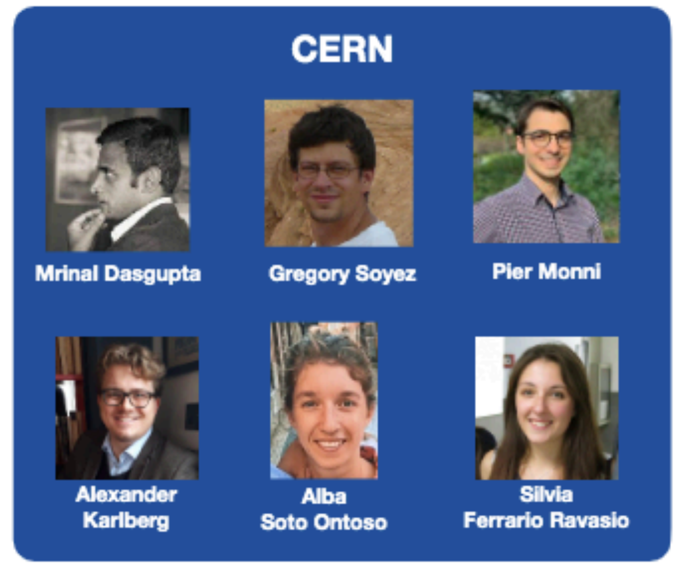


Plus correctness of virtual corrections to soft/collinear emissions

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

PanScales collaboration





PanScales

A project to bring logarithmic understanding and accuracy to parton showers

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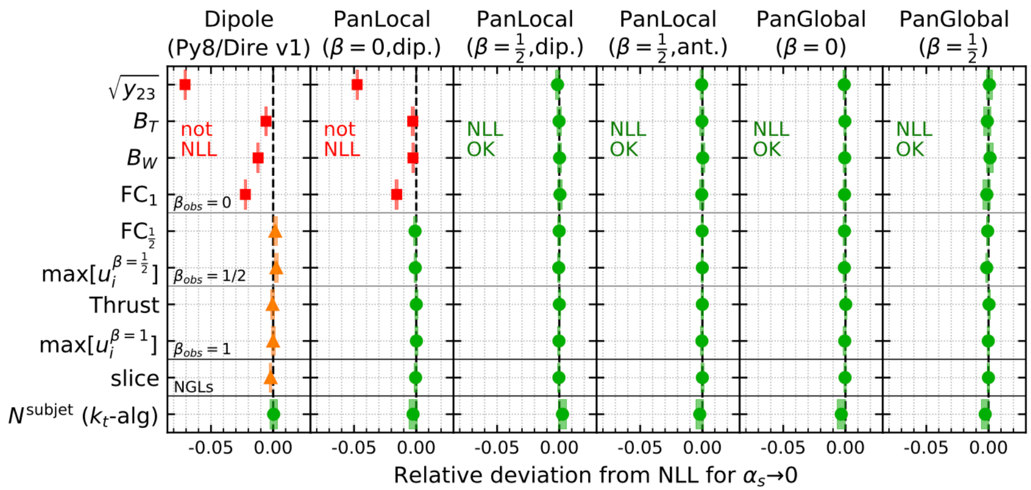
NLL showers step 1 : leading Nc



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

pp showers : van Beekveld, Ferrario Ravasio, Hamilton, Salam, Soto-Ontoso, Soyez, Verheyen, 2022.

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

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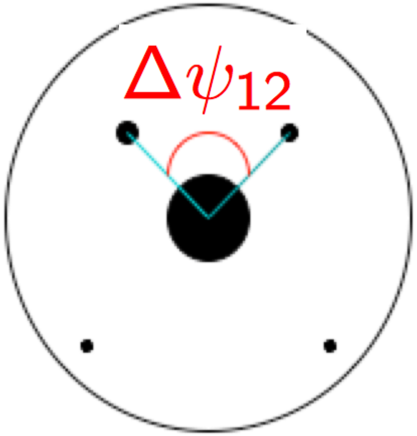
Lund observable for NLL recoil effect



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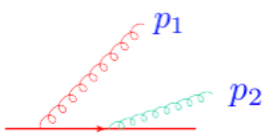

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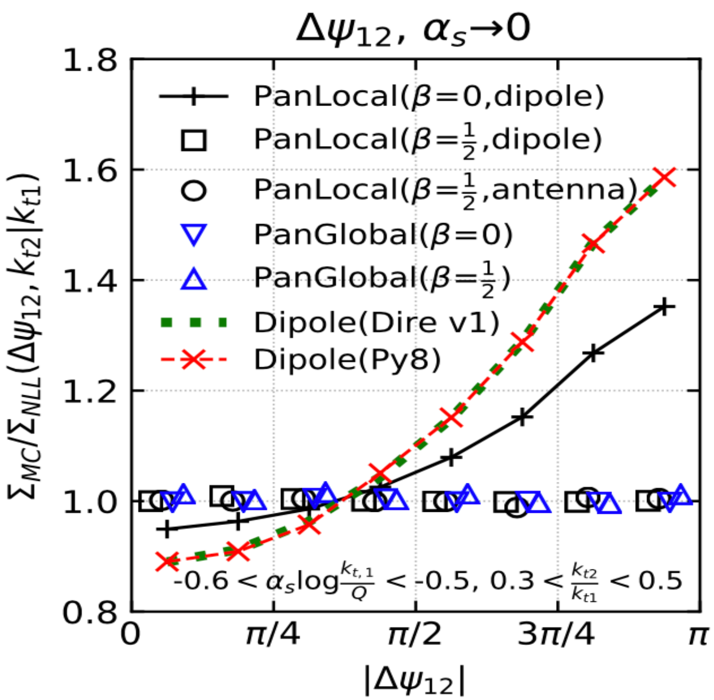
MD, Dreyer, Hamilton, Monni, Salam, Soyez 2020

- 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.

Lund observable for NLL recoil

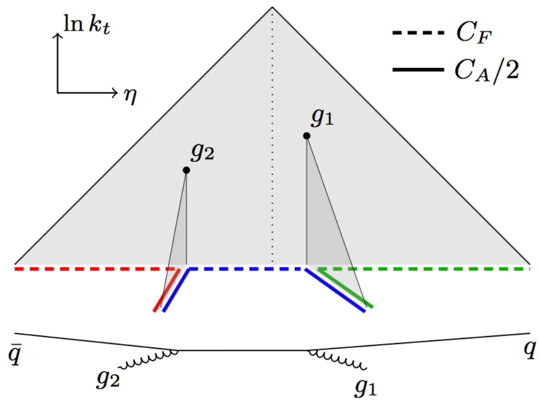


- Incorrect showers show a dependence on $\Delta\psi$
- There is an in principle significant effect

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

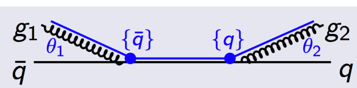


Not enough to just modify transition between dipole elements

- One sol. directly based on QCD coherence (Lund plane picture.)
  Hamilton,Medves, Salam, Scyboz, Soyez, 2020.

- 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.

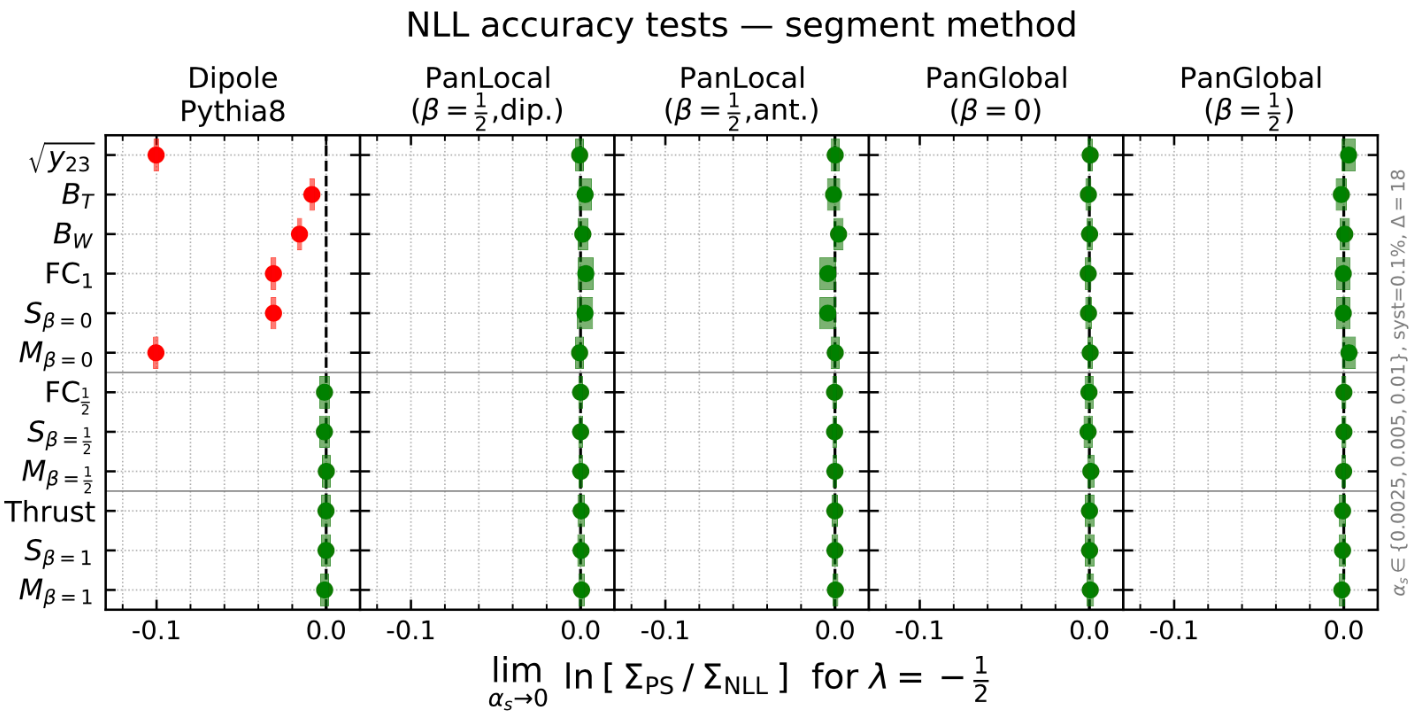
Keep track of the transitions between C_F and $C_A/2$ along any dipole



$$[-\infty; \frac{C_A}{2}; -\log\frac{\theta_1}{2}; C_F; \log\frac{\theta_2}{2}; \frac{C_A}{2}; \infty]$$

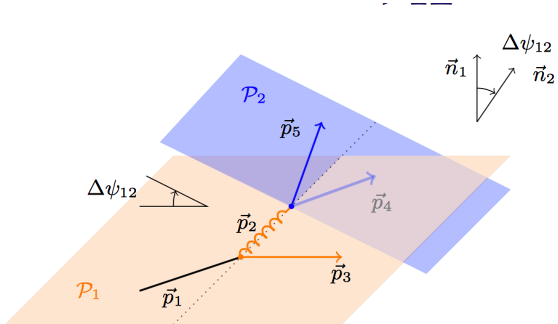
- Gives full colour LL and for a set of key (global) observables full colour NLL.

NLL (full colour)for global observables

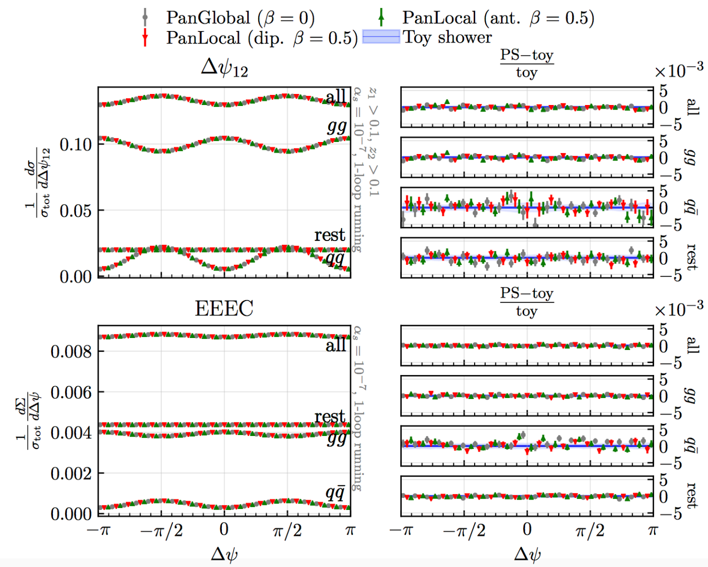


Hamilton, Medves, Salam, Scyboz, Soyez, 2020

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.

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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)