MANCHESTER 1824

The University of Manchester

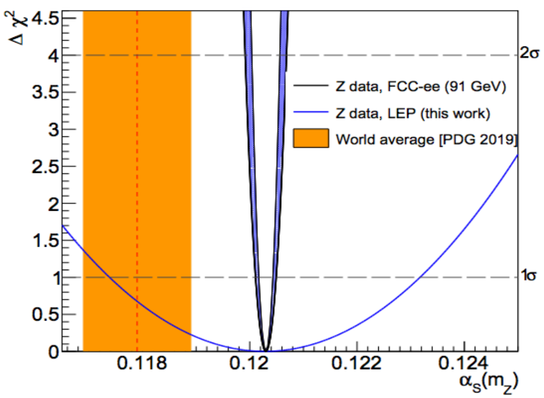
PanScales : setting new standards for parton shower accuracy

Mrinal Dasgupta
University of Manchester
(On behalf of the PanScales collaboration)

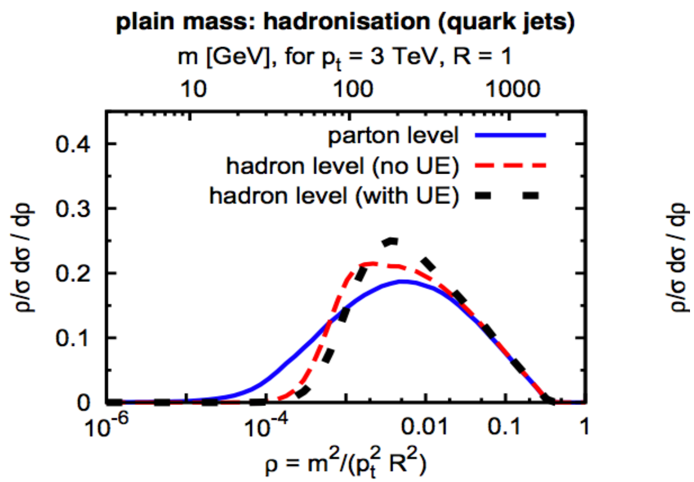
ECFA-UK workshop, Durham, September 23rd 2024

European Research Council
Established by the European Commission

Theory challenges from current and future colliders



Fits to EWPO. LEP versus FCC-ee predictions. **D'Enterria et al 2022**



MD, Fregoso, Marzani, Salam 2013.

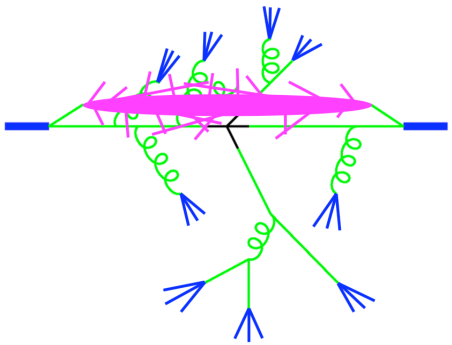
- Challenge from wealth of high precision data. Theory tools **must** keep up for physics program to reach its potential.
- Challenge from going to TeV scale and beyond. Direct sensitivity to rich structure of QCD and NP effects.

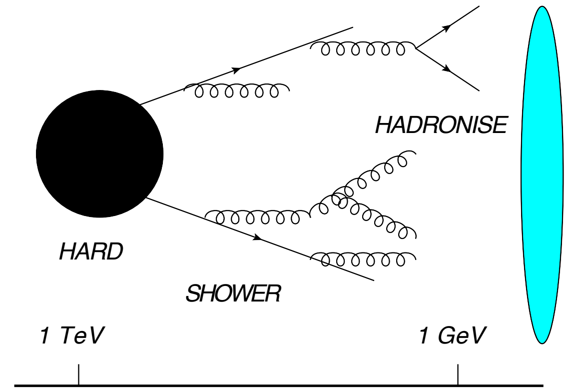
The University of Manchester

MANCHESTER 1824

Parton showers

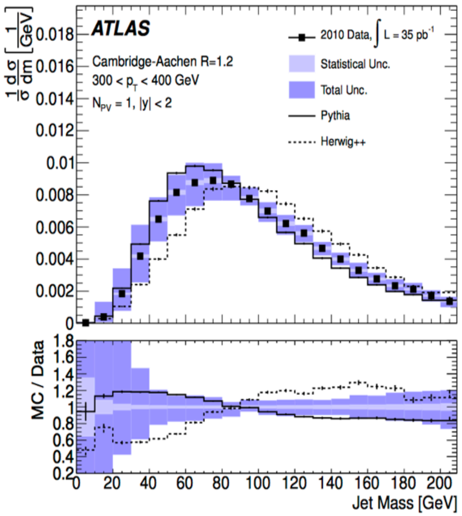
1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event



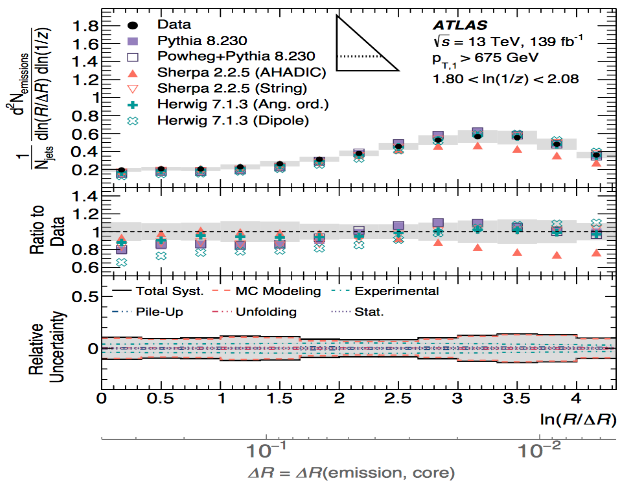


- Perhaps the **most crucial of theory tools** across all collider physics
- **Core component of all GPMCs** used in virtually all high energy collider analyses. Describe evolution over huge scale range (Tev down to 1 GeV).
- Beyond SM hard process **the only component directly connected to SM (QCD) Lagrangian**. Holds the key to precision in MC approach.

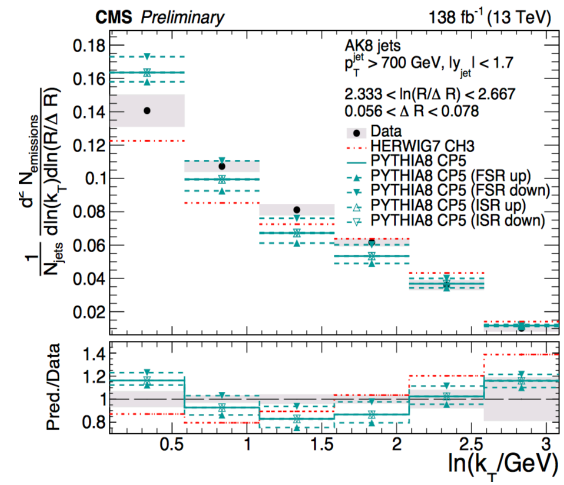
Shower differences



ATLAS 2011



ATLAS 2019



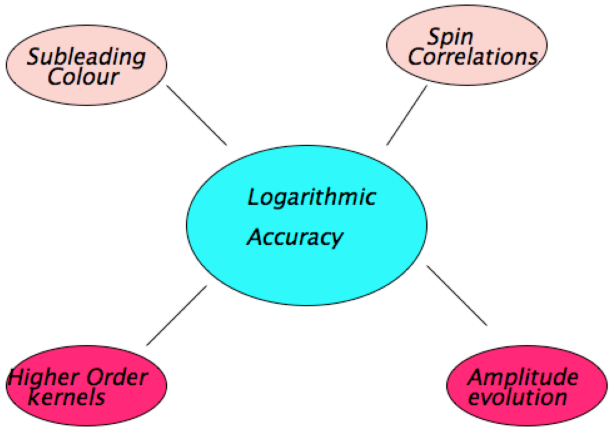
CMS 2023

- For long a limitation in pheno. studies.
- Spread between showers often taken as measure of uncertainty. Without concept of accuracy this loses meaning.
- Clear need to do better. Calls for systematic common framework to think about shower accuracy.

MANCHESTER 1824

The University of Manchester

Common framework: logarithmic accuracy



- Various improvements can be made to showers wrt spin, colour, higher-orders etc.
- But log accuracy gives framework to evaluate relevance of any improvement.
- Allows to meaningfully compare different showers.
- Dealing with log accuracy one meets all the other questions anyway.

MANCHESTER 1824

The University of Manchester

Logarithmic accuracy

$$\Sigma(Q) = \sum_n c_n \alpha_s^n$$

Single scale observable. **Accuracy specified by maximum n**.

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

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

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

Multiscale observable **with exponentiation. Accuracy depends on g_n**

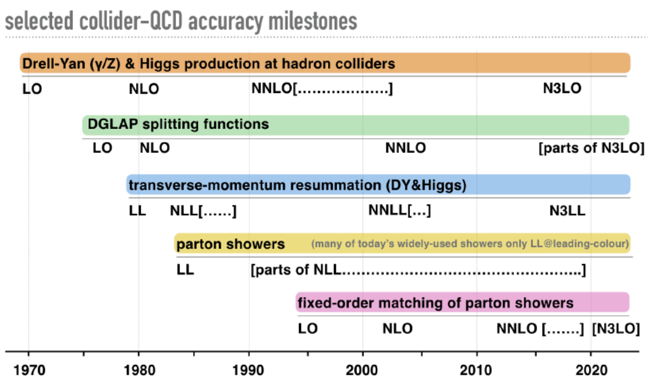
- g_1 is leading log (LL). Controls all double log (m= 2n) terms in expansion.
- Including g_2 gives NLL and g_3 is NNLL.
- **NLL is a must for accurate pheno**.

Catani, Trentadue, Turnock and Webber 1992

The University of Manchester

MANCHESTER 1824

Shower accuracy over decades



Taken from talk at Moriond QCD 2023 by G.Salam

- Understanding + systematically improving shower accuracy proved notoriously difficult.
- Danger most important tool might become our weakest link.

Some questions as of 2017

Can we :

0. Understand clearly accuracy of various showers? Somewhere in between LL and full NLL but where?

1. Identify simple clear criteria to achieve a given accuracy? Use these to construct NLL accurate showers.

2. Achieve our ambition to reach NNLL? (high risk part of project!)

3. Demonstrate the value of more accurate showers in phenomenology?

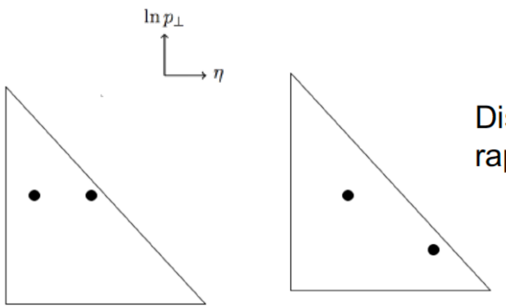
MANCHESTER
1824

The University
of Manchester

Step 0 : Understand accuracy of existing showers

Understanding shower accuracy

Commensurate k_t disparate rapidity. NLL config.



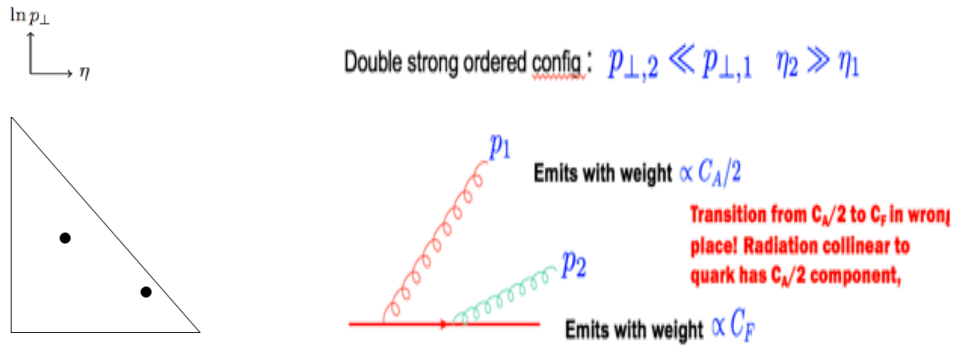
Disparate k_t and rapidity. LL config.

MD, Dreyer, Hamilton, Monni, Salam 2018

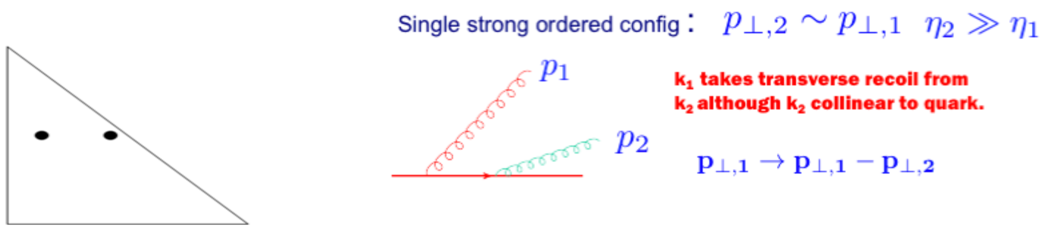
- Focussed on common class of "dipole " showers incl. Pythia8.
- Convenient to think in terms of "Lund" variables associated to QCD log divergences
- Surprising problems found for emissions widely separated in Lund plane. Both LL and NLL broken.

Recoil and colour problems

MD, Dreyer, Hamilton, Monni, Salam 2018



Incorrect LL for widely studied observables e.g. thrust albeit $\frac{1}{N_c^2}$ "colour suppressed"



Incorrect NLL for several classic observables

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

Failure to reproduce basic "independent emission" property of QCD matrix-element

MANCHESTER 1824

The University of Manchester

Possible choices on path ahead

A possible point of view:

- *For some of well known observables coefficients of LL and NLL failure found to be small-moderate (colour suppression, azimuthal averaging). Take comfort in this and work on something else?*

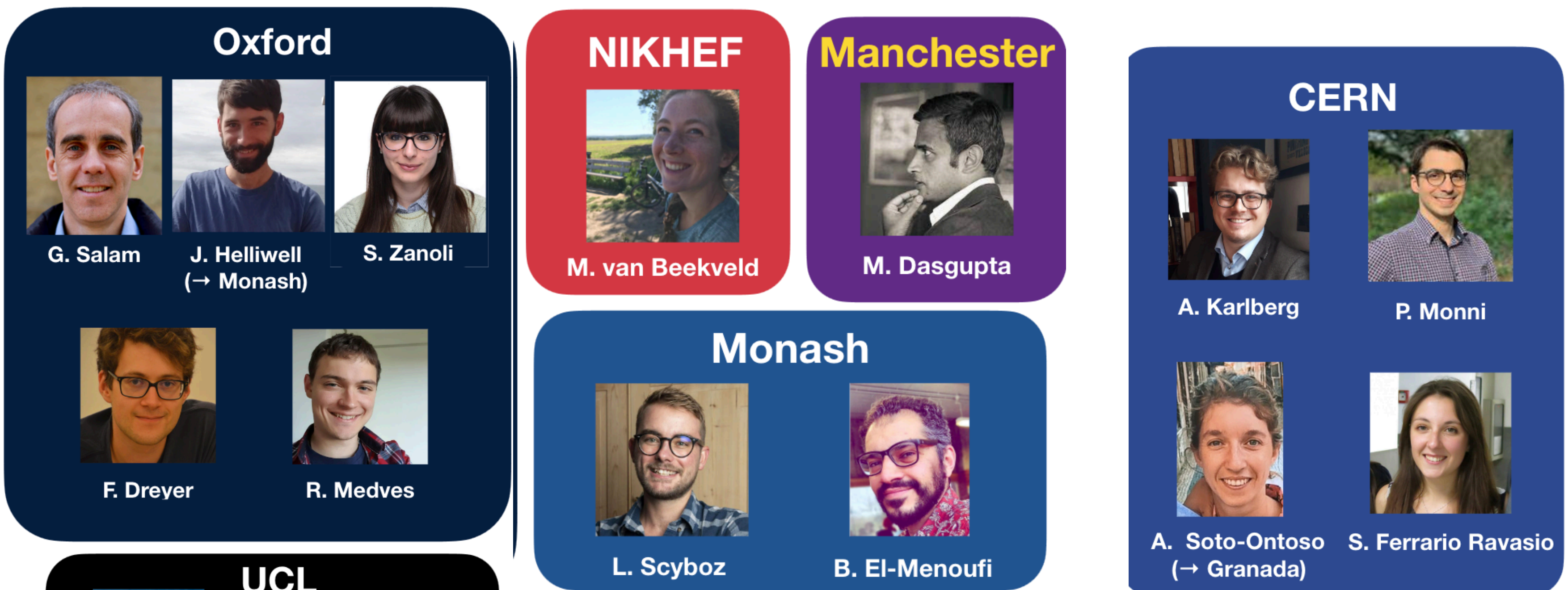
Approach we took:

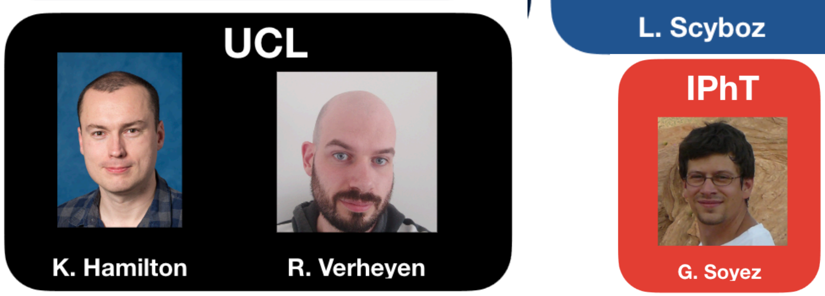
- *Failure to reproduce decades old analytic resummation results and basic QCD expectations for just 2 emissions are examples of serious flaws.*
- *Not difficult to find observables where effects can be substantial . Worry about complex machine learning related observables.*
- *With precision of theory tools under focus and future colliders on the horizon urgent need for progress*
- *To achieve more accurate NNLL showers a first step is to fix NLL problems.*

MANCHESTER 1824

The University of Manchester

PanScales : bringing logarithmic accuracy to showers





Current and past members of PanScales (Sept. 2024)

https://gsalam.web.cern.ch/gsalam/panscales

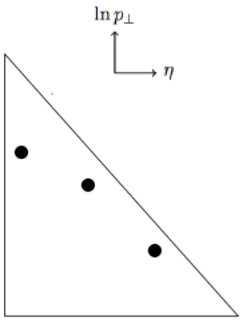
MANCHESTER
1824

The University of Manchester

Step 1: Criteria for shower accuracy and NLL goal

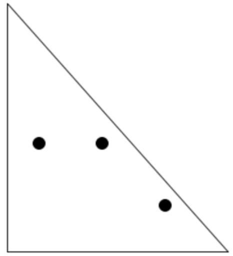
Accuracy criteria

- 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



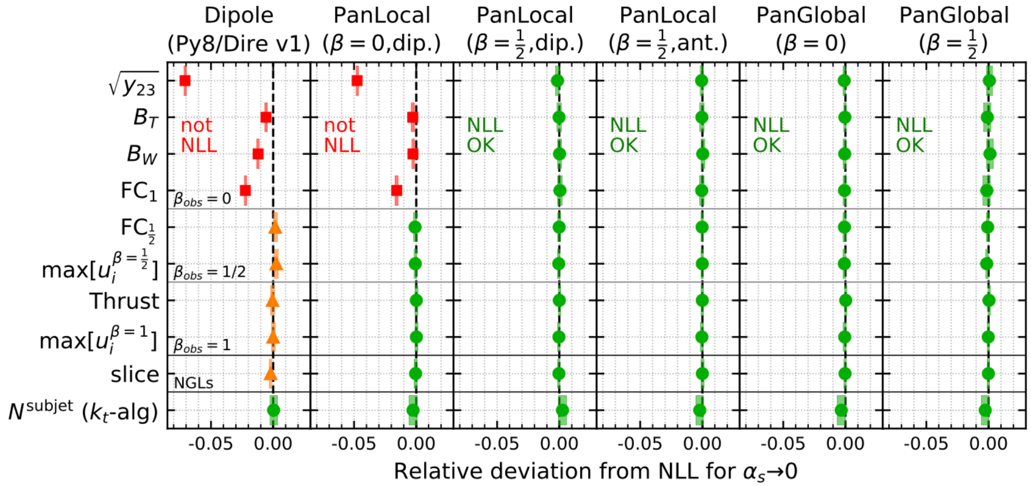
in limit where every pair of emissions is well separated in at least one of LP variables

Plus correctness of virtual corrections to soft/collinear emissions

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

Done via inclusion of suitable higher order analytic ingredients

NLL showers



Leading N_c :MD, Dreyer, Hamilton, Monni, Salam, Soyez 2020

Full Colour :Hamilton, Medves, Salam, Scyboz Soyez, 2020

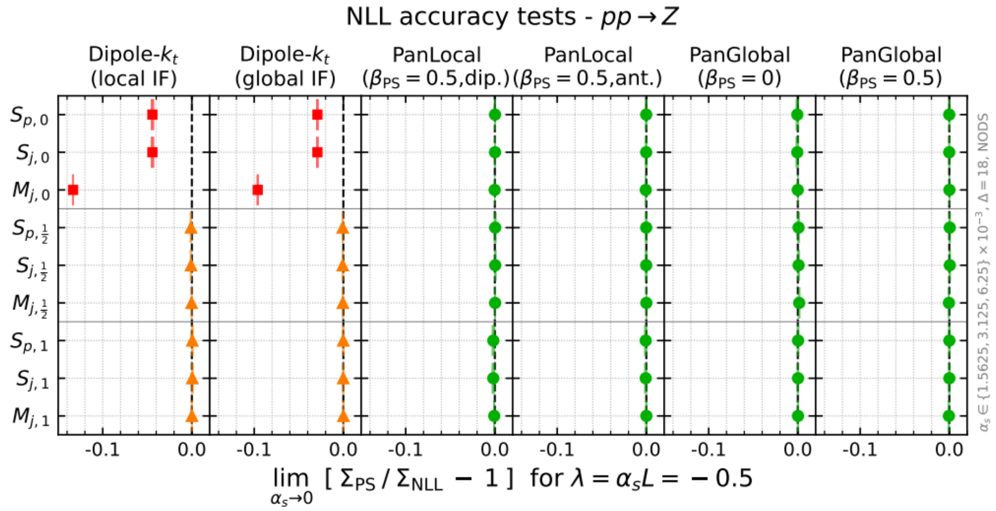
With spin corr. : Karlberg, Salam, Scyboz, Verheyen, 2021

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 shower ordering variable $v \sim k_t e^{-\beta|\eta|}$

NLL pp showers



van Beekveld, Ferrario Ravasio, Salam, Soto Ontoso , Soyez(and + Hamilton) 2022

- NLL accurate PanScales showers for pp collisions. Colour singlet production.
- NLL PanScales showers also achieved for DIS and VBF **processes van Beekveld, Ferrario Ravasio 2023**

- PanScales first validated NLL showers.

Other shower codes or algorithms with NLL achieved : Alaric (analytical and numerical NLL proof) Herren etal 2023. FHP shower, Forshaw Holguin Platezer 2020 (analytic proof for thrust). Likely NLL based on algo. : DEDUCTOR Nagy and Soper 2011.

Step 2 : The NNLL challenge

MANCHESTER 1824

The University of Manchester

Towards NNLL

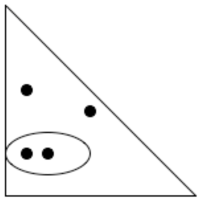
NNLL accuracy requires numerous highly non-trivial developments

- Go back to PanScales criteria. Now need to add

For NNLL accuracy :

shower ME ⟶ QCD result

in limit where pair of emissions come close in Lund plane



Ferrario Ravasio, Hamilton, Karlberg, Salam, Scyboz, Soyez 2023

Requires inclusion of higher-order splitting kernels in NLL shower.

We start with "double-soft" kernels describing soft emissions commensurate in angle. Catani and Grazzini 1998

MANCHESTER 1824

The University of Manchester

Towards NNLL

- Also NLL showers in soft limit make use of NLO corrected emission probability via using

.

$$\alpha_s^{\text{eff}} = \alpha_s \left(1 + K_{\text{CMW}} \frac{\alpha_s}{2\pi}\right)$$

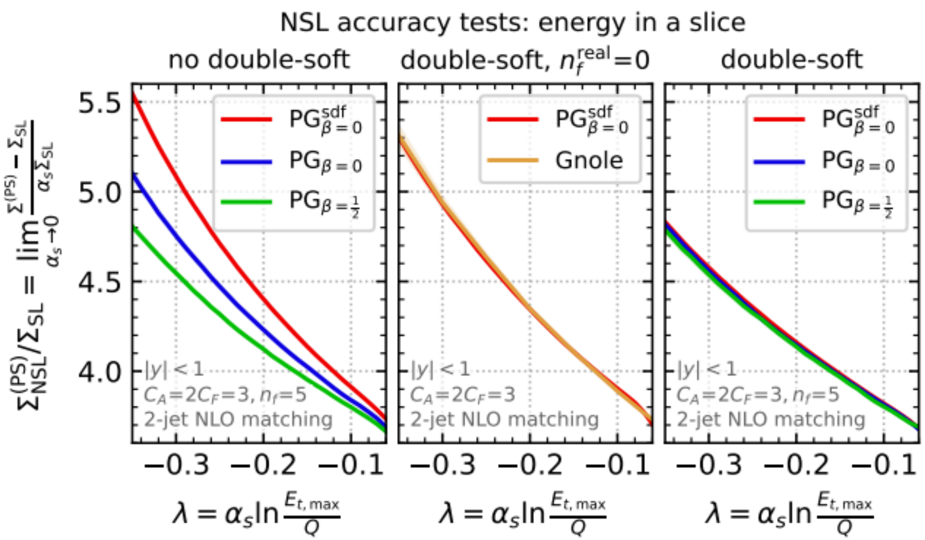
Related to correct inclusion of virtual corrections.
Same K_{CMW} similarly appears also in analytic resummation.

- Beyond NLL in soft large angle region for most panscales showers this needs correction via a shower ΔK

- These soft corrections already give NNLL for a few observables

Ferrario Ravasio, Hamilton, Karlberg, Salam, Scyboz, Soyez 2023

First shower results beyond NLL



Ferrario Ravasio, Hamilton, Karlberg, Salam, Scyboz, Soyez 2023

Also needs NLO 2 jet matching. Hamilton, Karlberg, Salam, Scyboz, Verheyen 2023.

- Get NSL terms e.g. for class of rapidity slice energy flow type observables $\alpha_s^n L^{n-1}$

- Corresponding analytic resummations only recently appeared!

Banfi, Dreyer, Monni 2021,2022. Becher, Schalch, Xu, 2023.

- Shower gave first ever NSL resummation of slice with full n_f

MANCHESTER 1824

The University of Manchester

NNLL showers for event shapes

Based on earlier groundwork plus considerable insight and substantial further effort to bring together in shower

Groundwork :
1. Prior inclusion of double soft kernels plus ΔK
2. Analytic understanding of higher order resummation ingredients in general obs. independent context. MD and El-Menoufi 2021. van Beekveld, MD, El-Menoufi, Helliwell, Monni 2023. Banfi, El-Menoufi and Monni 2018

AND

Further understand subtleties in connection between shower and analytic resummation ingredients beyond soft limit

MANCHESTER 1824

The University of Manchester

First NNLL showers for event shapes

CERN-TH-2024-057, OUTP-24-03P

A new standard for the logarithmic accuracy of parton showers

Melissa van Beekveld,[1] Mrinal Dasgupta,[2] Basem Kamal El-Menoufi,[3] Silvia Ferrario Ravasio,[4] Keith Hamilton,[5] Jack Helliwell,[6] Alexander Karlberg,[4] Pier Francesco Monni,[4] Gavin P. Salam,[6,7] Ludovic Scyboz,[3] Alba Soto-Ontoso,[4] and Gregory Soyez[8]

[1] *Nikhef, Theory Group, Science Park 105, 1098 XG, Amsterdam, The Netherlands*
[2] *Department of Physics & Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom*
[3] *School of Physics and Astronomy, Monash University, Wellington Rd, Clayton VIC-3800, Australia*
[4] *CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland*
[5] *Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK*
[6] *Rudolf Peierls Centre for Theoretical Physics, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK*
[7] *All Souls College, Oxford OX1 4AL, UK*
[8] *IPhT, Université Paris-Saclay, CNRS UMR 3681, CEA Saclay, F-91191 Gif-sur-Yvette, France*

We report on a major milestone in the construction of logarithmically accurate final-state parton showers, achieving next-to-next-to-leading-logarithmic (NNLL) accuracy for the wide class of observables known as event shapes. The key to this advance lies in the identification of the relation between critical NNLL analytic resummation ingredients and their parton-shower counterparts. Our analytic discussion is supplemented with numerical tests of the logarithmic accuracy of three shower variants for more than a dozen distinct event-shape observables in $Z \to q\bar{q}$ and Higgs $\to gg$ decays. The NNLL terms are phenomenologically sizeable, as illustrated in comparisons to data.

2024 NNLL paper submitted to PRL

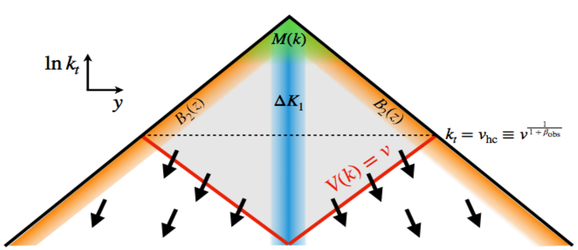
NNLL showers for event shapes

- Now shower emission needs more h.o. coeffs:

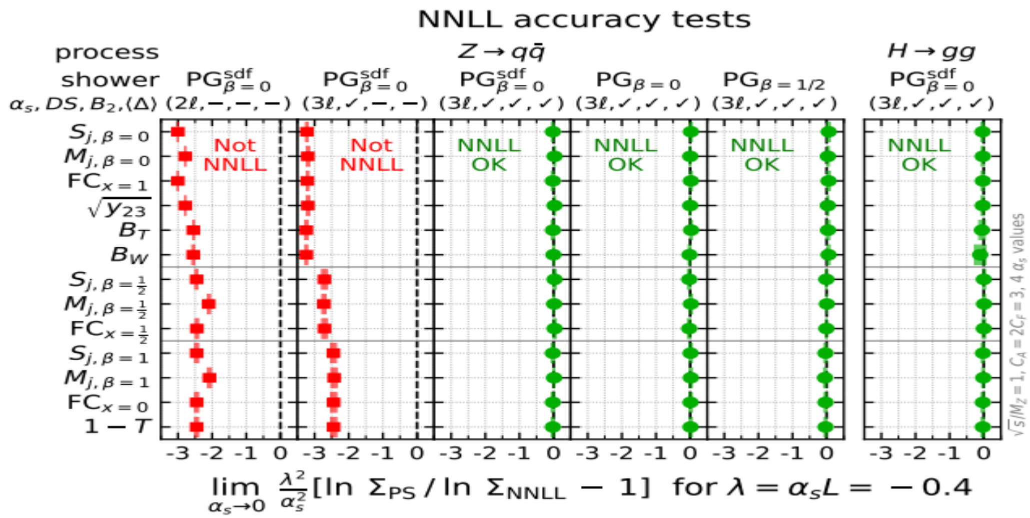
$$\alpha_{\text{eff}} = \alpha_s \left[1 + \frac{\alpha_s}{2\pi} \left(K_1 + \Delta K_1(y) + B_2(z) \right) + \frac{\alpha_s^2}{4\pi^2} K_2 \right],$$

van Beekveld et al 2024

More NLO resummation coefficients similar to resummation counterparts. Includes effect of hard collinear emissions.
But differ due to shower emission “drifts” reflecting post v pre-branching emission kinematics.



NNLL showers for event shapes



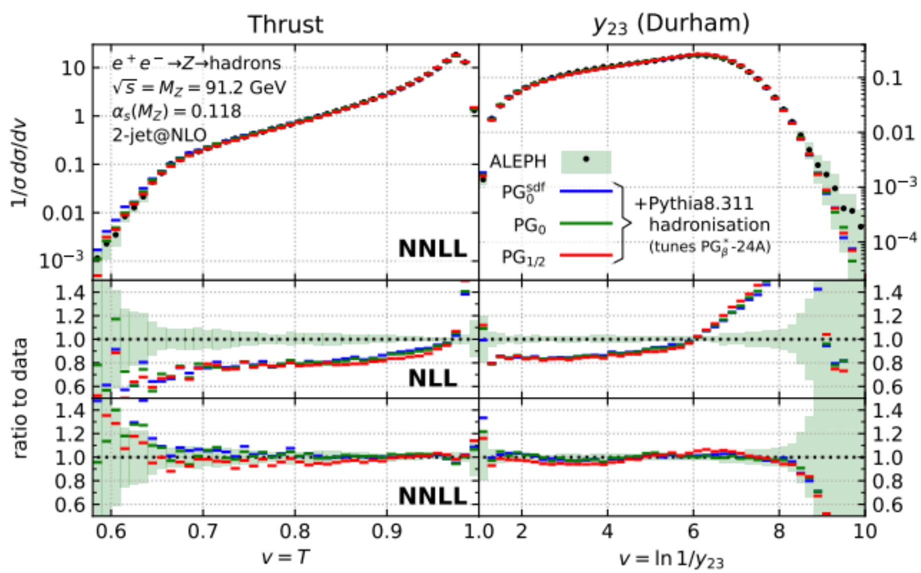
Several observables
2 processes

van Beekveld et al 2024

- Understanding drift contributions proved final piece of complex NNLL puzzle
- Led to analytical and numerical proofs of NNLL accuracy for final state showers for global event shape variables

$$
\begin{aligned}
\frac{\Sigma^{\mathrm{PS}}(v)}{\Sigma^{\mathrm{resum}}(v)} - 1 = 8C_F \Big\{ & - \langle \Delta_y \rangle T_2(v,1) \\
& + \left[\langle \Delta_y \rangle + \langle \Delta_{\ln k_t} \rangle \right] T_2(v_{\mathrm{hc}},1) \\
& + \langle \Delta_{\ln k_t} \rangle \left[\frac{1}{\beta_{\mathrm{obs}}} T_2(v, v_{\mathrm{hc}}) - T_2(v_{\mathrm{hc}},1) \right] \\
& + \left[\langle \Delta_y \rangle - \frac{1}{\beta_{\mathrm{obs}}} \langle \Delta_{\ln k_t} \rangle \right] T_2(v, v_{\mathrm{hc}}) \Big\} = 0
\end{aligned}
$$

LEP phenomenology : a first look



van Beekveld et al 2024

In pheno context our NNLL corrections are substantial
First look at ALEPH data : NNLL corrections bring showers in good agreement with data.

Our studies use $\alpha_s(M_z) = 0.118$ Contrasts with larger value ~0.13 needed by Pythia and some NLL PanScales variants.
Encouraging signs but not conclusive until some currently missing effects are included (NLO 3 jet matching, quark masses)

MANCHESTER 1824

The University of Manchester

Summary and outlook

Go back to 2017 questions to see where we stand:

0. Understand clearly accuracy of various showers? Somewhere in between LL and full NLL but where? ✔ 2018

1. Identify simple clear criteria to achieve a given accuracy? Use these to construct NLL accurate showers. ✔ 2021

2. Achieve our ambition to reach NNLL? (high risk part of project!) ✔ 2024 (**N.B. :Fully general NNLL still needs extra step but we have proof of concept for that** (van Beekveld et al 2024). **Plus need NNLL for ISR)**

3. Demonstrate the value of more accurate showers in phenomenology?

First steps show some promising signs. But much work for the near future

On the table still : Complete NNLL final state picture, NNLL for initial state, fixed-order matching progress, quark masses, pheno….. Exciting times ahead!