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# Parton Showers

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# Outline

- Introductory remarks on showers
- Current approaches and known limitations.
- Understanding shower accuracy
- Recent developments
- What to expect in the near future?

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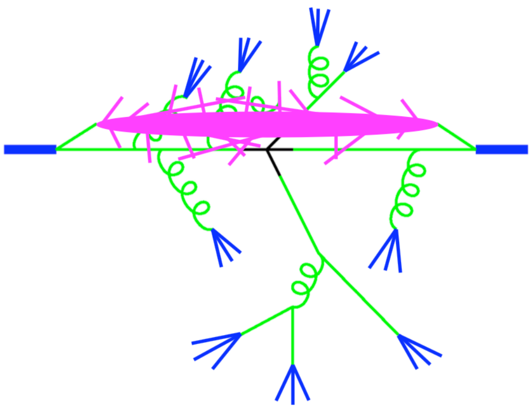
# Parton showers

**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 SM hard process **the only component directly connected to SM (QCD) Lagrangian**. Holds the key to precision in MC approach.

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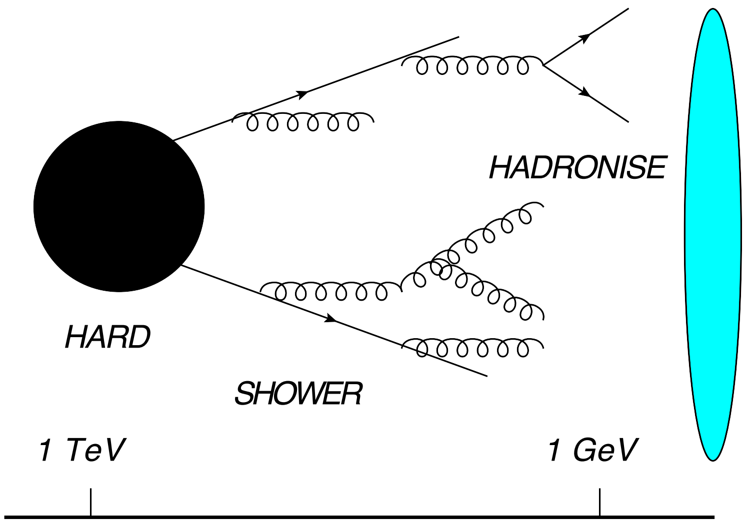
# Showers and multiple scales

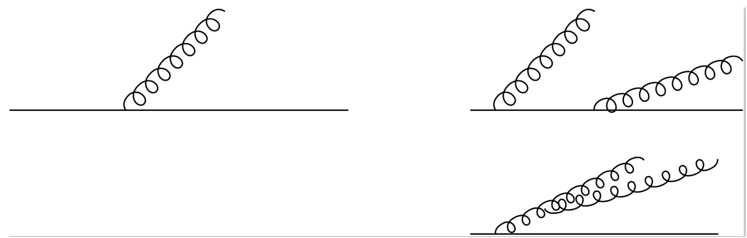



- Any LHC process involves huge scale hierarchy.
- **Showers describe evolution from TeV scale** of hard process **down to ~ 1 GeV**.
- Many **observables sensitive to multiple disparate scales**.

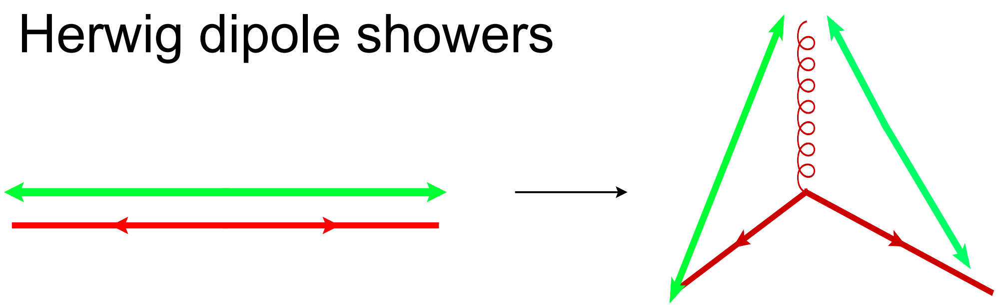
# Different approaches

- Can broadly classify as being based on concept of **parton evolution** via 1 to 2 splittings e.g. Angular Ordered Herwig Shower

Fails to capture class of soft large angle effects



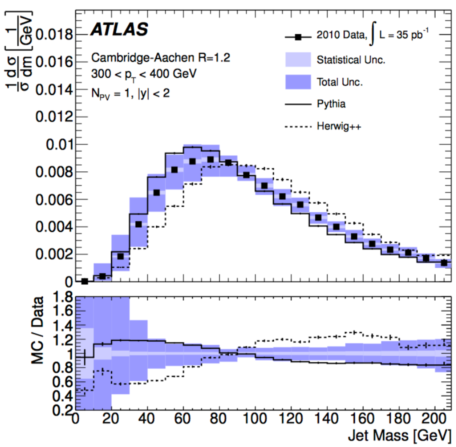
- Or 2 to 3 splittings **of colour dipoles e.g.** Pythia 8, Sherpa and Herwig dipole showers

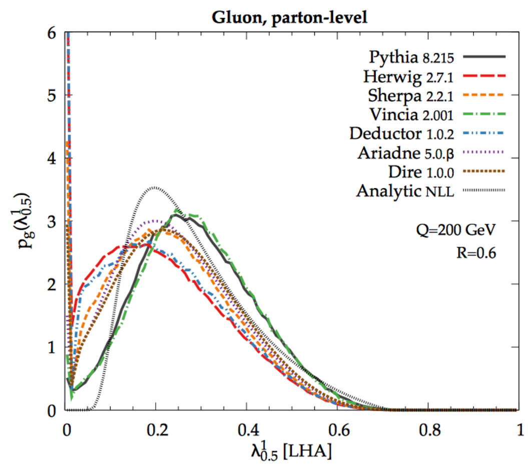


Other examples : DiRe, Vincia, PanScales showers

Formulated in large Nc limit. Question about how to handle recoil.

# Shower limitations and issues




Gras et. al. 2017

Differences between showers are a key limiting factor in today's phenomenology

- Leading source of systematic uncertainty on Jet Energy Scale that enters numerous experimental measurements.

- Machine learning uses complex observables sensitive to wide range of scales – reliant on showers

- How do we address this, given shower models make different choices?
  **NEEDED** ***: A concrete framework to discuss shower accuracy***

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# Logarithmic accuracy

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

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

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

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

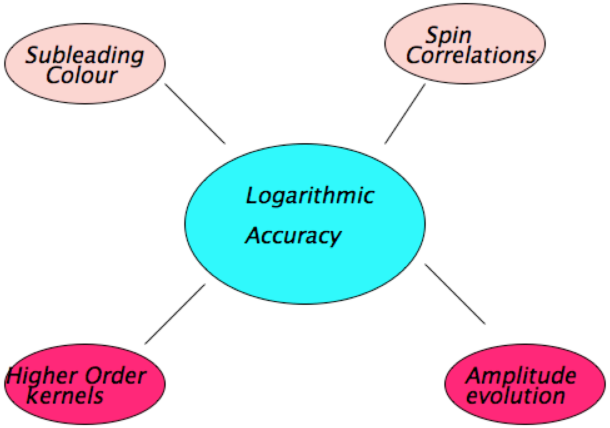
$$\Sigma(Q, vQ) \sim \exp[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \cdots]$$

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

# Improving shower 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.

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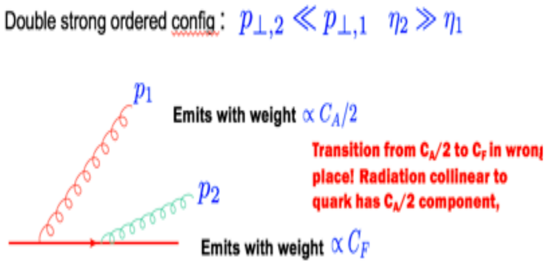
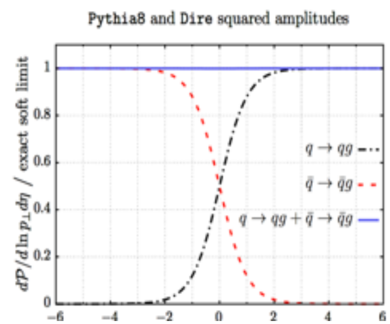
# Logarithmic accuracy of showers




MD, Dreyer, Hamilton, Monni and Salam 2018

- For decades showers generally stated to have LL accuracy.
- Commonly believed that they give NLL for several important observables (based on inclusion of NLL ingredients like the CMW scheme for coupling)
- Known that AO showers don’t give general NLL
- Recent studies revealed issues with dipole showers (e.g. Pythia 8, Dire v1). **LL accuracy broken beyond leading Nc. NLL accuracy broken even at leading Nc.**

***So where do we go from here?***

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# Recent Progress

**(Selected highlights with apologies for omissions)**

# Logarithmic accuracy : key questions

- Identify principles for NLL?

- Can we understand log accuracy of a wider range  of showers?

- Can we construct NLL showers from first principles?

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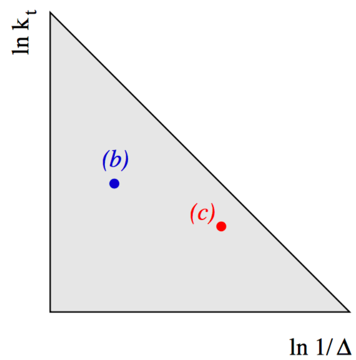
# Principles for NLL



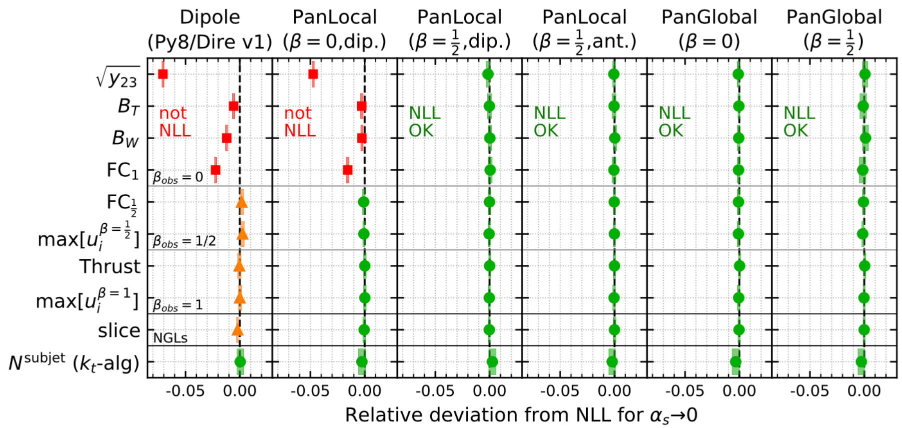

- Reproduction of tree level matrix elements when emissions strongly ordered in at least one of 2 possible logarithmic variables

→ Emissions well separated in the Lund plane $e^{-D} \ll 1$

- Test of overall correctness of virtual corrections through reproduction of NLL resummation for common observables.

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

# New NLL showers



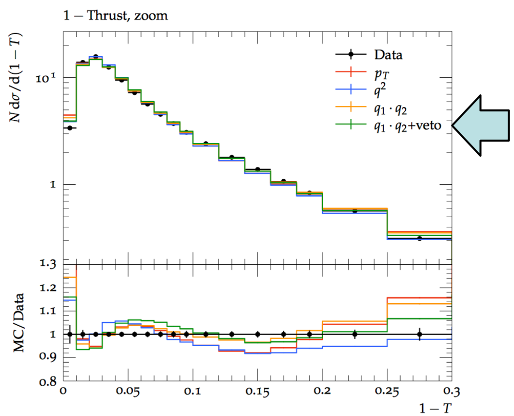

Initially formulated in leading Nc limit

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

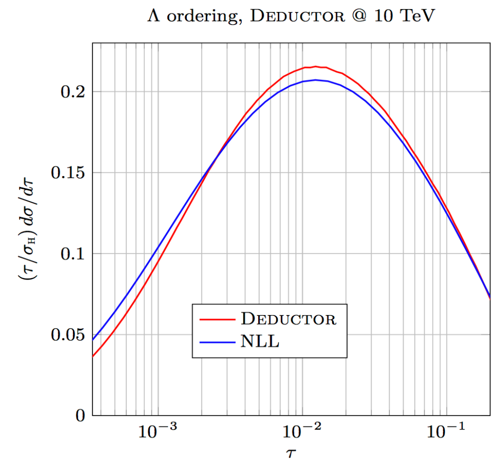
- Two new families of dipole showers : **PanGlobal** and **PanLocal** based on global or dipole-local recoil
- General ordering variable varied through parameter $\beta$
- **Tested against all-orders NLL resummation**

**PanScales collaboration : van Beekveld, MD, Dreyer, El-Menoufi, Ferrario Ravasio, Hamilton, Helliwell, Karlberg, Medves, Monni, Salam, Scyboz, Soto Ontoso, Soyez, Verheyen.**

# Exploring accuracy of other showers




Modified Dot prod. preserving scheme maintains log accuracy and describes data well




- Study of recoil and understanding of log accuracy in Herwig and impact on phenomenology Bewick, Ferrario Ravasio, Richardson, Seymour 2019
- Deductor shower tested for NLL accuracy for thrust variable. OK for Λ (time) ordering but not fully conclusive for $k_t$ Nagy and Soper 2021
- New Forshaw-Holguin-Platzer (FHP) dipole shower has global recoil scheme. Did analytic study of thrust. Potentially NLL but no numerical studies of this yet. Forshaw, Holguin, Platzer 2020

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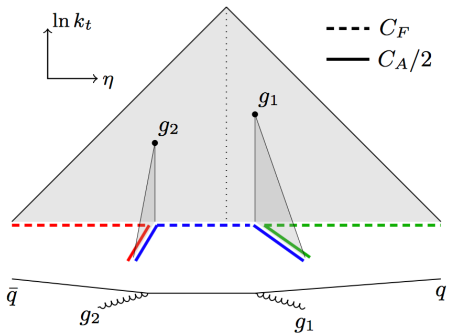
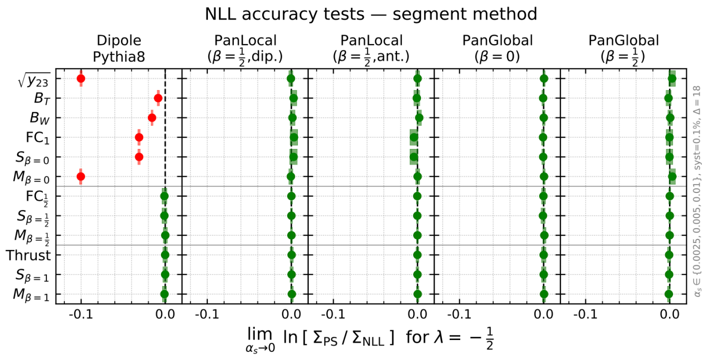
# Subleading colour




- Several past efforts to include subleading colour corrections in dipole shower framework. (See e.g. arXiv: 1808.00332, arXiv: 1806.10102)
- Subset of PanScales collab. devised 2 schemes to improve colour treatment. Based on QCD coherence and nested double soft matrix-element corrections. Hamilton, Medves, Salam, Scyboz, Soyez, 2020
- FHP have also introduced method based on QCD coherence Forshaw Holguin Platzer 2020

# Full colour log accuracy




Hamilton, Medves, Salam, Scyboz, Soyez, 2020

PanScales proposals implemented in PanLocal and PanGlobal frameworks.

Demonstrate LL accuracy at full colour (FC) and FC NLL for double logarithmic global observables.

FHP algorithm includes full colour effects for LL terms but falls short of NLL. At present does not treat $g \to q\bar{q}$ splittings. Forshaw Holguin Platzer 2020

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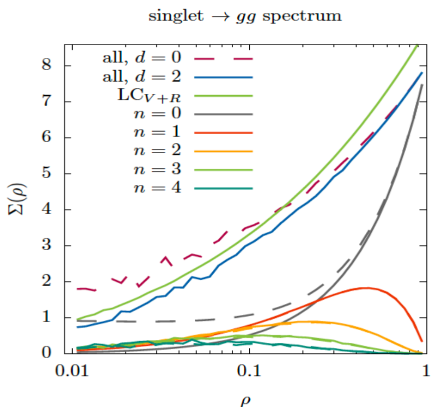
# Amplitude evolution

- In some cases current approaches cannot capture full colour at NLL (single-log) accuracy.
- Examples include observables sensitive to soft large angle emission (non-global obervables) and event shapes in dijet production in hh collisions.
- But missing $\mathcal{O}\left(\frac{1}{N_c^2}\right)$ NLL terms are effectively similar to NNLL terms.
- To capture them one needs **amplitude level evolution**.

# Amplitude evolution




CVolver for H to gg gaps between jets. Consistent with calculation by Hatta and Ueda

- Based on soft gluon evolution of amplitude and its complex conjugate
- Two current approaches are Deductor and CVolver Nagy and Soper 2007 De Angelis, Forshaw, Platzer 2020
- Practical results from Deductor use an approximation to full colour - LC+
- Recent first results from CVolver for interjet energy flows. Full colour treatment of real emissions with subleading colour expansion in virtual terms.

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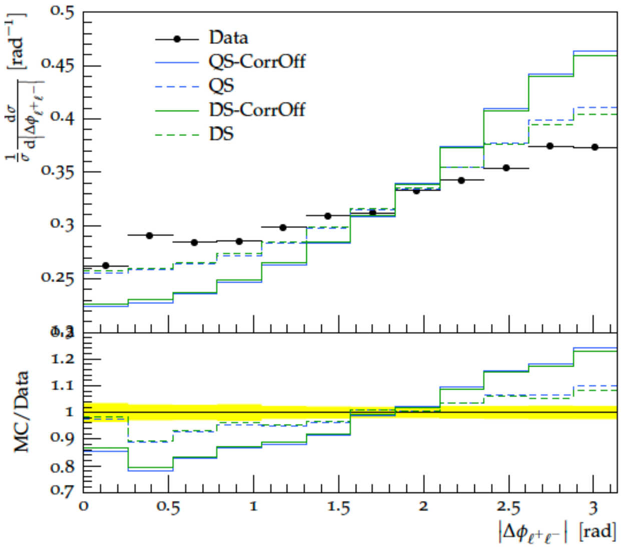
# Spin correlations in showers

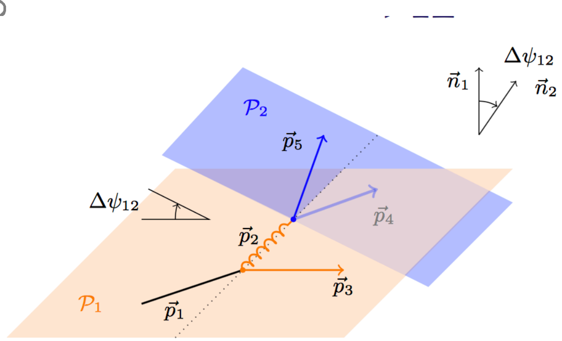



Herwig 7 showers with and without spin corr. Compared to CMS data.

Richardson and Webster 2018.

- Spin corr. needed for specific observables e.g. those exploiting azimuthal correlations. Important for achieving NLL criteria.
- Algorithm due to Collins and Knowles used to implement spin corr. in the showers in Herwig 7. Richardson and Webster 2018
- Dipole shower implementation needs particular care.

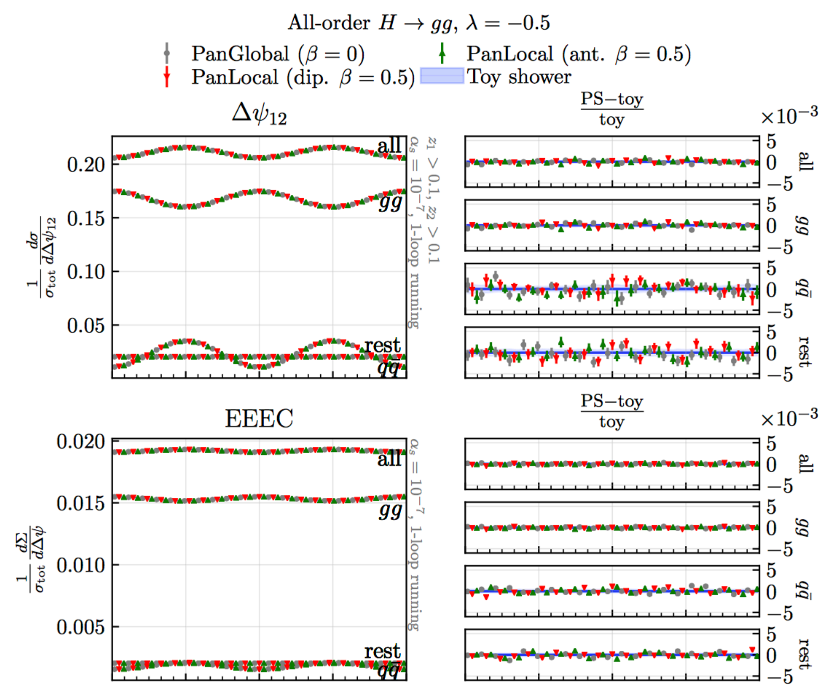
# Spin in PanScales showers




Also uses C-K algo.

Karlberg, Salam, Verheyen, Scyboz 2021

- Azimuthal correlations defined using leading $k_t$ splitting in primary and secondary Lund plane
- New variables to test spin corr. in showers



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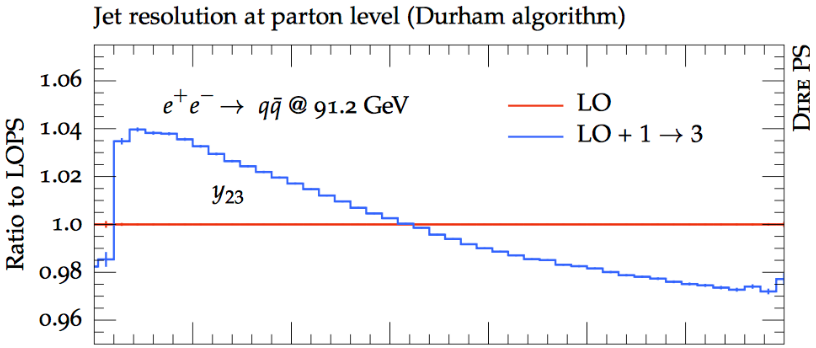
# Higher order showers




Gellersen, Hoche, Prestel 2021

- From log accuracy viewpoint going to NNLL will need consistent inclusion of higher order splitting kernels triple-collinear (1 to 3) and double soft kernels.

- Inclusion of splitting kernels in triple collinear and double soft limits studied by different groups. Hoche and Prestel 2017, Hoche, Prestel, and Krauss 2017, Li and Skands 2017. Dulat, Hoche, and Prestel 2018.

- But this also increases fixed-order accuracy of shower

# Future prospects

What may we expect from shower accuracy in the near future?

- NLL e+e- has been essentially been reached. Soon expect pp showers with similar accuracy.
- NNLL showers are now a realistic goal.
- These developments will go together with other improvements e.g. subleading colour. Also keep an eye on amplitude level shower codes.
- Improved shower accuracy will also lead to more development of matching techniques to fixed-order calculations.
- Phenomenology with more accurate showers is an exciting prospect.