

Recent developments in Parton Showers

High Precision for Hard Processes 2026

Daniel Reichelt, CERN

6 October 2026

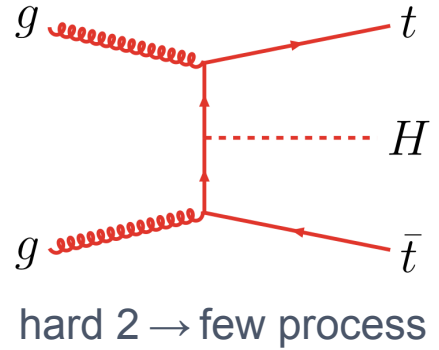


Funded by the
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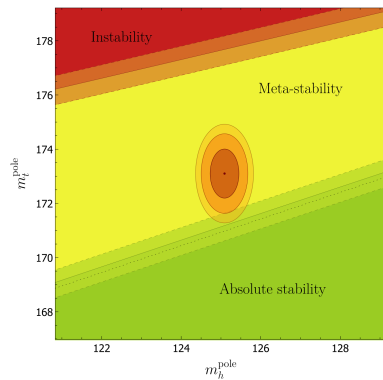


Event generators – theory to experiment

THEORY

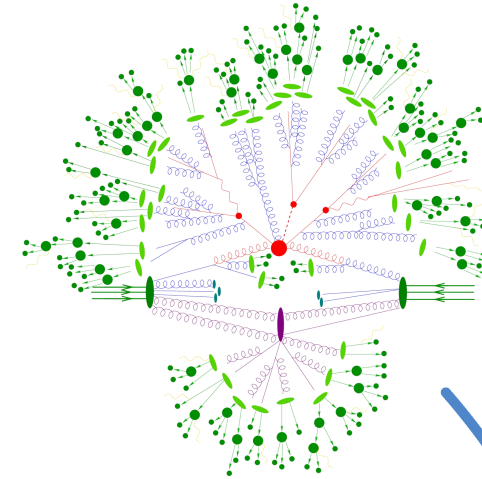


FUNDAMENTAL PHYSICS QUESTION

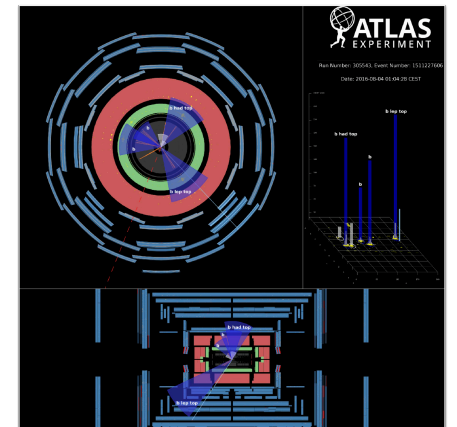


EVENT GENERATOR

factorised simulation:
hard process
parton shower
PDF / UE
hadronisation
QED
hadron decays



EXPERIMENT
hadrons, jets and leptons in a detector



Parton Showers

GENERAL PICTURE

1 Universal soft and collinear limits

$$|\mathcal{M}_{n+1}|^2 \simeq |\mathcal{M}_n|^2 \frac{\alpha_s}{2\pi} \frac{dt}{t} dz P(z)$$

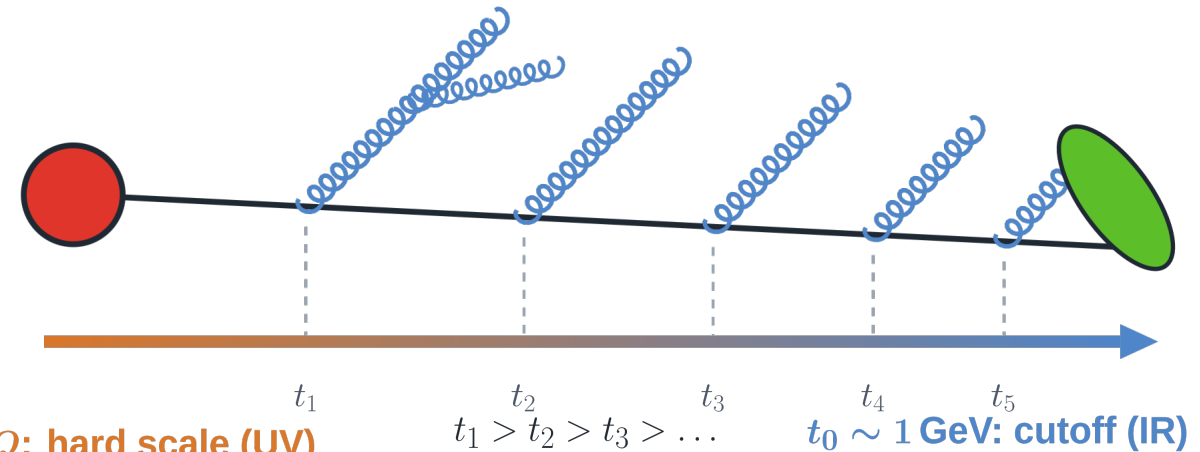
2 No-splitting probability

$$\Delta(t, t') = \exp \left[- \int_{t'}^t \frac{d\tilde{t}}{\tilde{t}} \int dz \frac{\alpha_s}{2\pi} P(z) \right]$$

3 Applied iteratively

draw scale according to Δ , construct emission and choose **recoil** scheme

EVOLUTION: FROM THE HARD SCALE TO THE CUTOFF



Q : hard scale (UV)

• Matching/Merging: MC@NLO, POWHEG

[\[Frixione, Webber '02\]](#) [\[Nason '04\]](#)

[\[Frixione, Nason, Oleari '07\]](#)

CKKW, CKKW-L, MLM

[\[Catani et al. '01\]](#) [\[Lönnblad '02\]](#)

[\[Mangano, Moretti, Pittau '01\]](#)

• Fragmentation: interface to Lund String (Pythia) or Cluster (Herwig, Sherpa) model

[\[Andersson et al. '83\]](#) [\[Webber '84\]](#)

Outline

1 NNLO matching – frontier and new ideas

2 Improved NLO matching

3 Shower foundations

Disclaimer

I will show a selection of works from different groups. I tried to collect new ideas and developments in favour of reviewing matured results, sorry if my selection cuts unfavourably on your favourite topic.

NNLO matching – frontier and new ideas

NNLO matching: status and frontier

Challenge: current showers do not match NNLO divergence structure, mostly slicing-based approaches combined with resummation or higher-order Sudakovs

Geneva

[Alioli et al. '13] ...

MiNNLO_{PS}

[Monni et al. '19] ...

UN²LOPS

[Höche et al. '15] ...

Vincia

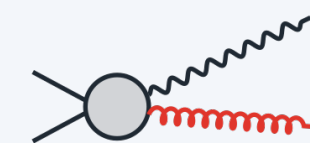
[Campbell et al. '21]

[Skands, Preuss '23]

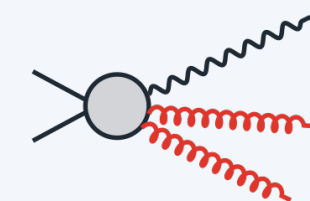
[El-Menoufi et al. '24]



0-jet

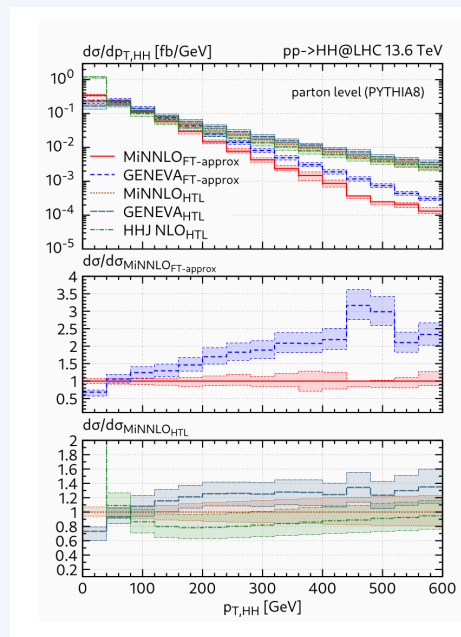


1-jet

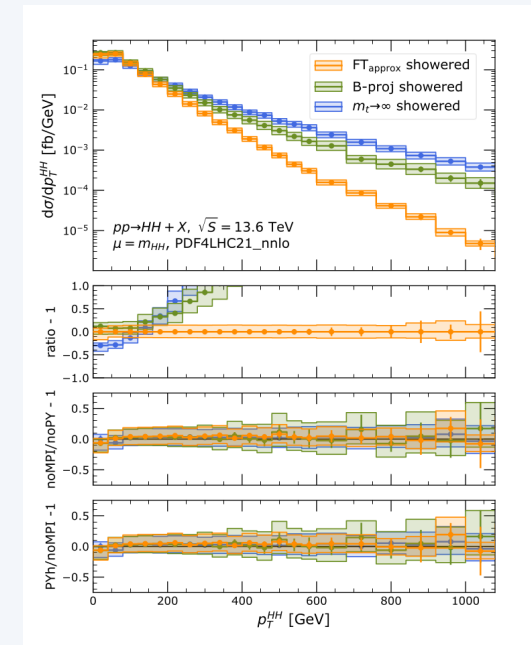


2-jet

Frontier example: Higgs pairs in heavy top limit vs approximate full theory



[Garosi et al. '26]



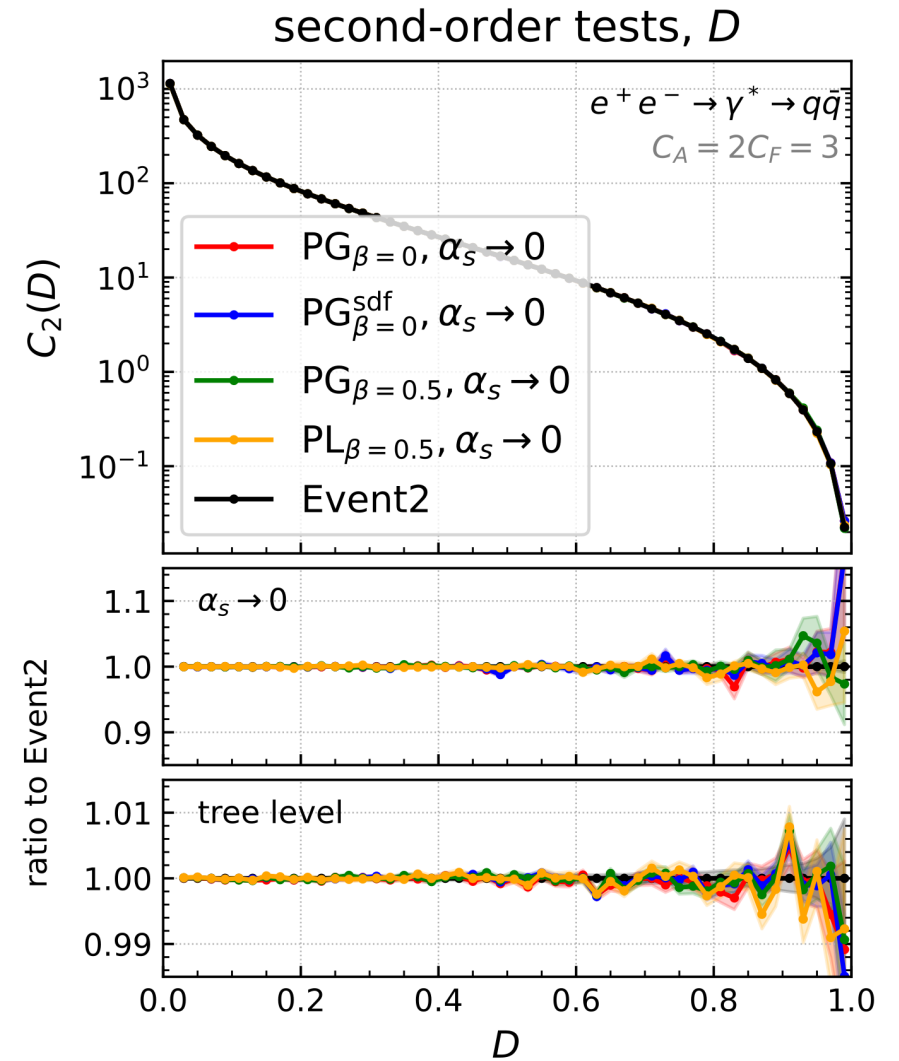
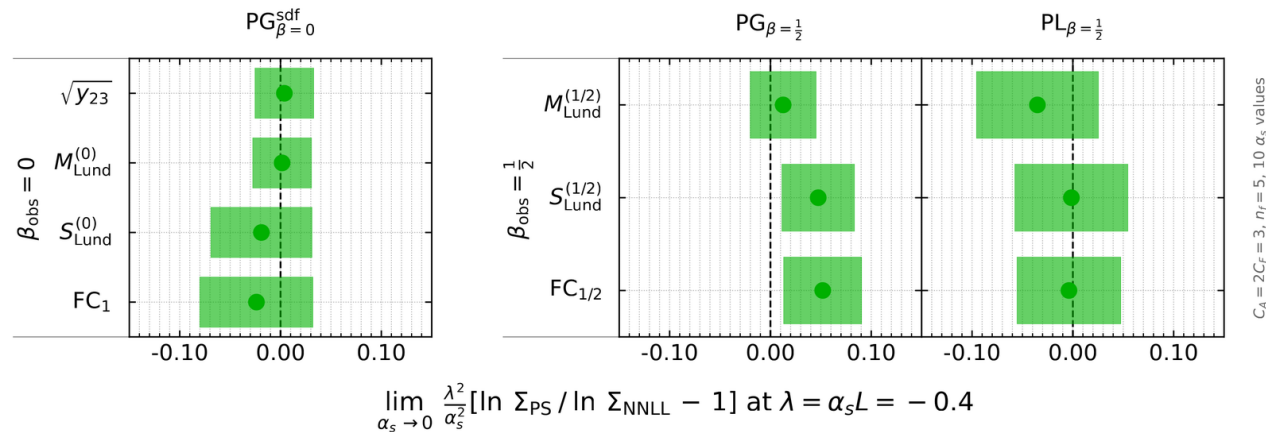
[Alioli et al. '25]

Matching beyond NLO in PanScales

Matching beyond NLO with log-accurate showers

[N. Schalch, QCD@LHC '26]

- double-real subtraction based on PanScales NNLL showers
- generate 4-parton point from PS and reweight
- numerically check against fixed order, point-by-point against double-soft splitting in PanScales, and for preservation of NNLL resummation



Towards NNLO in a shower-inspired scheme

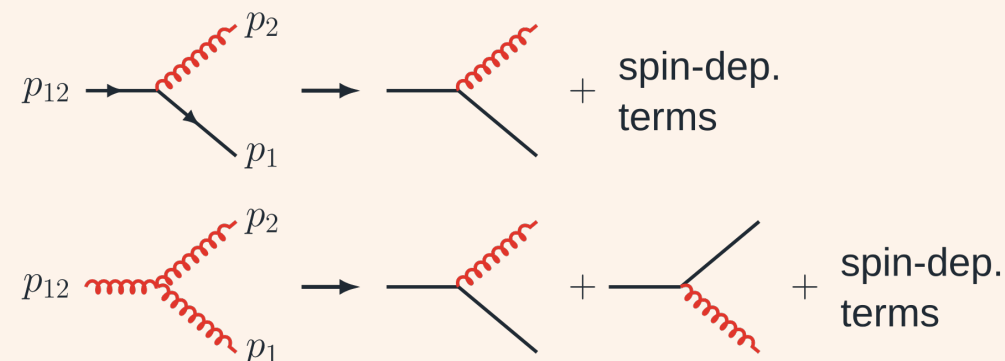
Foundation

- splitting functions **without soft or collinear limits**: scalar part + remainders

[\[Campbell et al. '25\]](#)

- **massive** splittings, new two-gluon radiators

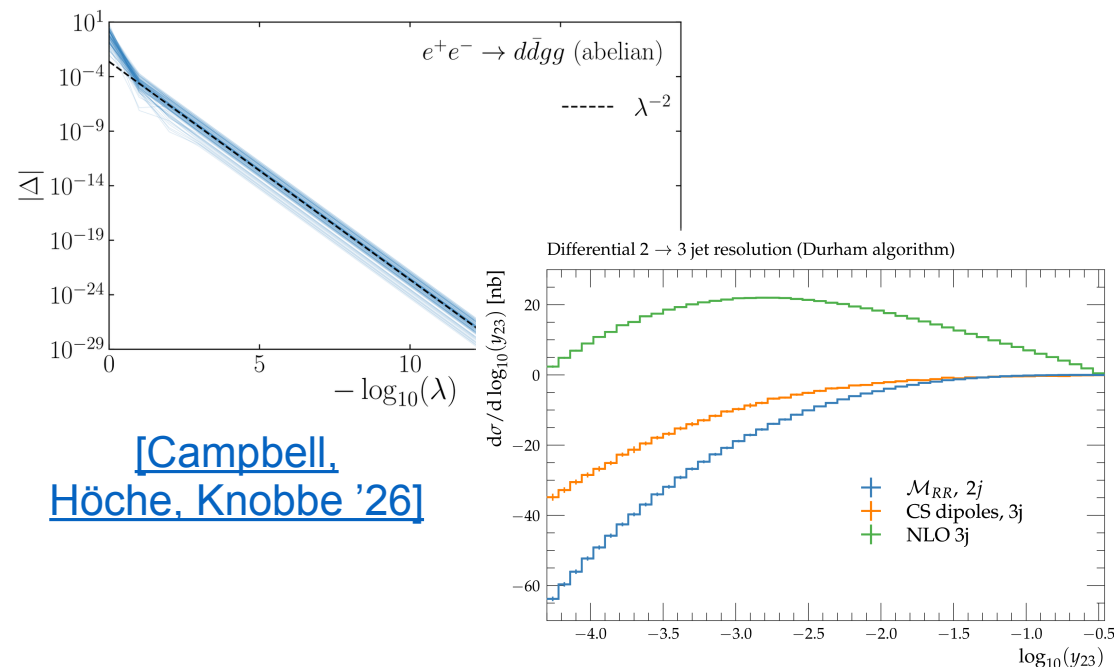
[\[Höche et al. '25\]](#)



Double-real corrections in a shower-inspired scheme

[\[Campbell, Höche, Knobbe '26\]](#)

- **local NNLO subtraction** for colour-singlet decays
- **partial fractioning** instead of sectorisation; iterated Alaric kinematics
- double-real remainder for $e^+e^- \rightarrow q\bar{q}$ **finite** in single and double unresolved limits
- Monte-Carlo convergence studied



[\[Campbell, Höche, Knobbe '26\]](#)

Information Theory for Precision Input

QCD theory meets information theory

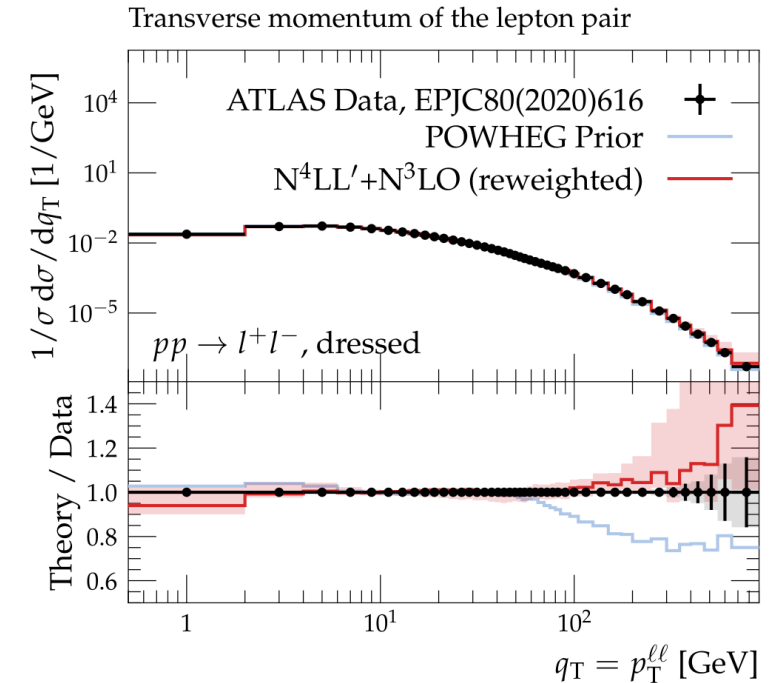
[\[Assi et al. '25\]](#) [\[Assi, Lee, Thaler '26\]](#)

- reweight MC to precision calculations, using **information-theoretic difference** between distributions
- could use any (number of) observables known to high precision
- **strictly positive weights**
- proof of concept: thrust in e^+e^-

Drell–Yan from low to high transverse momentum

[\[Assi et al. '26\]](#)

- state-of-the-art application: reweight Drell–Yan samples used at the LHC to $N^3\text{LO} + N^4\text{LL}'$
- can include **EW** and **lattice** information



Precision results enter **fully differential event generation** with positive weights — complementary to matching

Improved NLO matching

Positive-weight NLO matching

Why positive weights?

- negative weights reduce effective statistics: $N_{\text{eff}} = \left(\sum_i w_i \right)^2 / \sum_i w_i^2 = N (1 - 2f_-)^2$
- appear in modern MC through subtraction schemes, virtual corrections, PDFs beyond LO, ...

KrkNLO: matching without subtraction

[Sarmah, Siódmok, Whitehead '24, '25]

- reweight showered LO events, PDFs in the 'Krk' factorisation scheme

MAcNLOPS [Nason, Salam '21] [Che, Frederix '26]

- rescale S-events in favour of negative H events

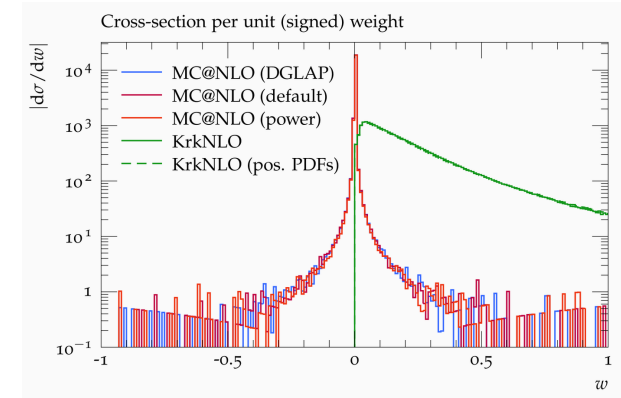
ESME [van Beekveld et al. '25]

- converts R-S integral into event wise integer weight, negative ones are higher order

MC@NLO from Born events

[El Farkh, Frederix, Gouighri '26]

- reweight unweighted Born events to the full S-event weight with large folding



[Sarmah, Siódmok, Whitehead '25]

Dealing with negative weights

cell resampling, ARCANE, neural and statistical reweighting, folding:

[Andersen et al. '24] [Andersen et al. '26] [Doherty et al. '26] [Shyamsundar '25, '25] [Nachman, Noll '25]
[Palmer, Kronheim '25] [Valassi '26]

Resonance awareness

Structure of subtraction scheme:

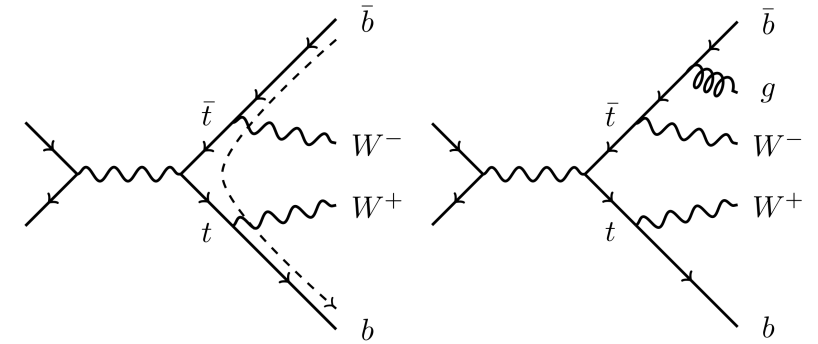
$$\sigma = \int d\Phi_n^{(d)} (B_n + V_n) + \int d\Phi_{n+1}^{(d)} R_{n+1} = \int d\Phi_n^{(4)} (B_n + V_n + I_n) + \int d\Phi_{n+1}^{(4)} (R_{n+1} - S_n)$$

defining S_n in the $(n+1)$ -parton phase space requires an **arbitrary (!) kinematics map**

Resonances

- assume a subset of momenta $(\tilde{p}_W, \tilde{p}_b)$ is identified to come from a resonance: dominant diagrams contain the **propagator** $\left[\left((\tilde{p}_W + \tilde{p}_b)^2 - m_t^2 \right)^2 + m_t^2 \Gamma_t^2 \right]^{-1}$
- let b emit a gluon, $\tilde{p}_W, \tilde{p}_b \rightarrow p_W, p_b, p_g$: **can change the propagator significantly**, unless
 $\tilde{p}_W + \tilde{p}_b = p_W + p_b + p_g$

(**not satisfied in standard, local dipole schemes!**)



Well-recognised problem, several solutions

[\[Ježo, Nason '15\]](#) [\[Ježo et al. '16\]](#) [\[Ferrario Ravasio et al. '18\]](#) [\[Ježo, Lindert, Pozzorini '23\]](#) [\[Höche, Liebschner, Siegert '19\]](#) [\[Denner et al. '26\]](#) [\[Höche, DR '26\]](#)

Resonance-aware MC@NLO

MoCaNLO + Pythia 8

[Denner et al. '26]

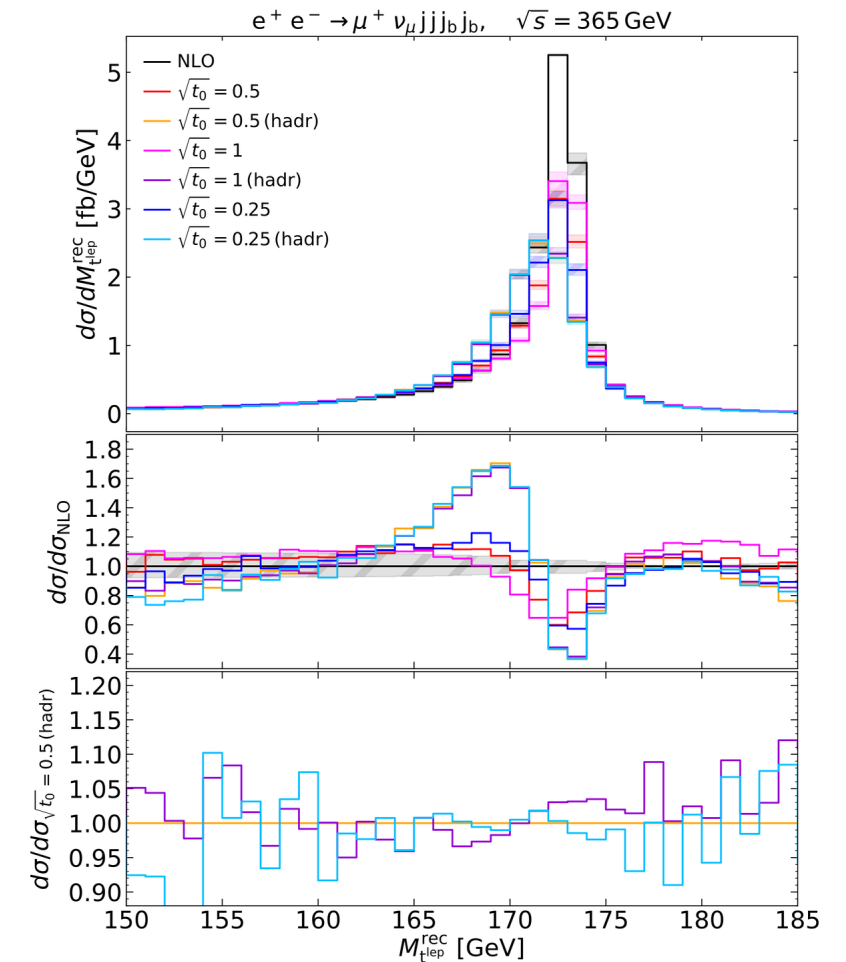
- **full off-shell** NLO QCD for $e^+e^- \rightarrow t\bar{t}$ with semi-leptonic decays
- MC@NLO adapted to Catani–Seymour subtraction with **dedicated counterterms** for production, decay and singly-resonant dipoles

Sherpa + Alaric

[Höche, DR '26]

- $e^+e^- \rightarrow W^+W^-b\bar{b}$ at NLO, matched with S-MC@NLO
- exploit general formulation of **Alaric recoil**: can choose any subset of hard momenta, choose remaining particles from resonance

Shower, subtraction and matching must agree on the **kinematics map**

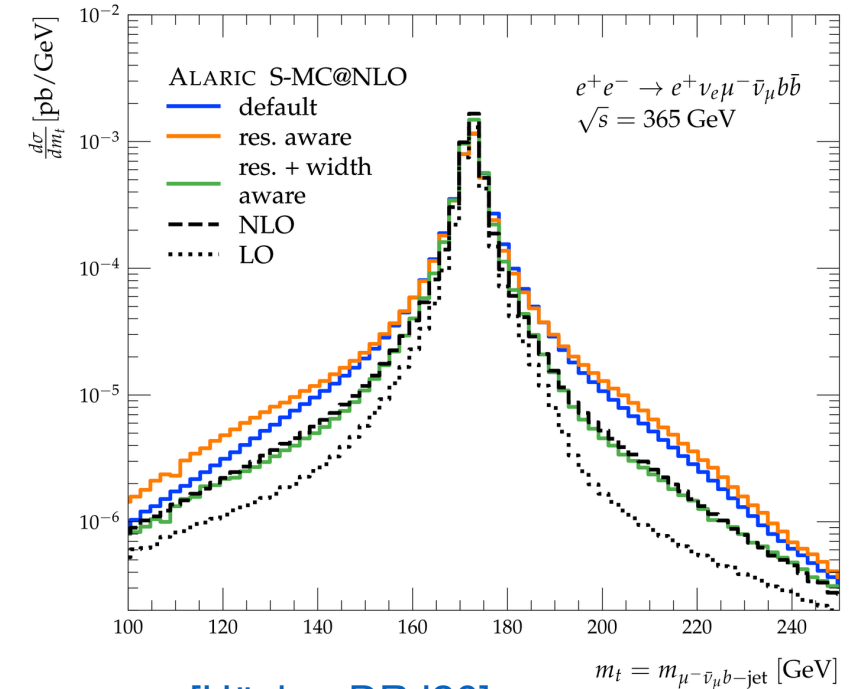
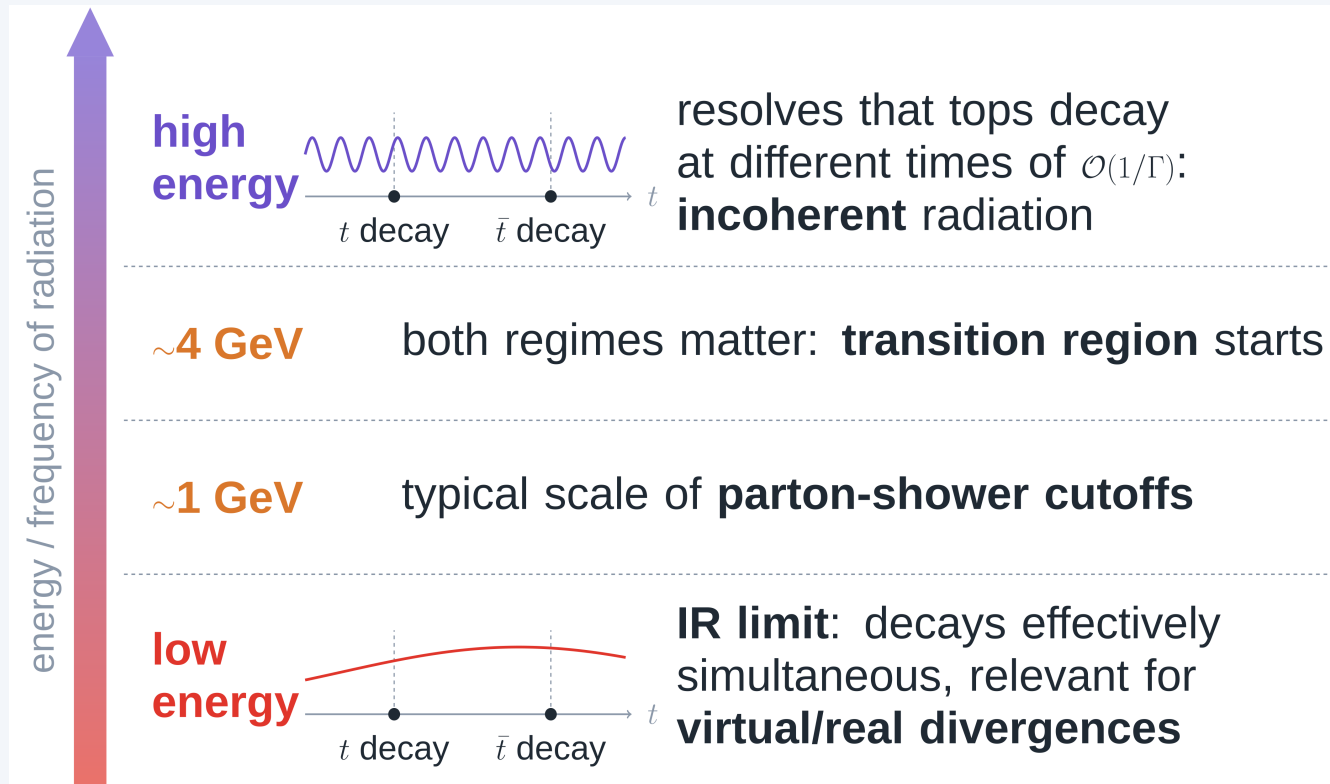


[Denner et al. '26]

Width awareness

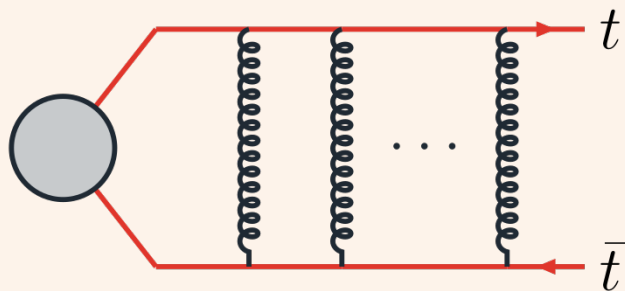
Width-aware evolution in Alaric

[Dokshitzer et al. '92] [Orr, Stirling '95] [Khoze, Sjöstrand '94]
[Höche, DR '26]



Interpolation between regimes
calculable, first-order QCD
result agrees with **semi-classical expectation**

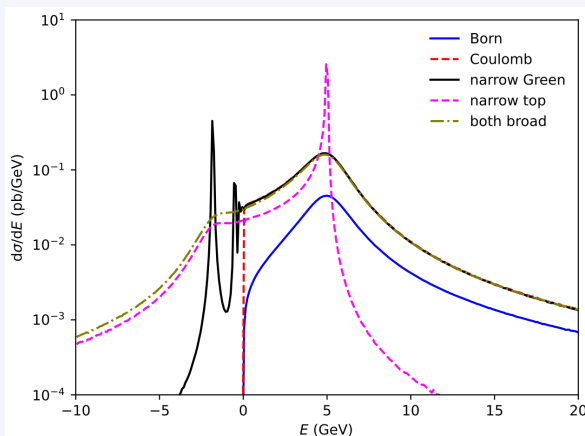
Top pair threshold



- near threshold, $M_{t\bar{t}} \approx 2m_t$: **enhanced perturbative corrections** from gluon exchange between the tops, computable to all orders
- non-relativistic **Green's functions**: quasi-bound toponium below, Coulomb enhancement above threshold
- simulation in MG5_aMC [Fuks et al. '21, '24]

Sjöstrand, Khoze, Preuss '26

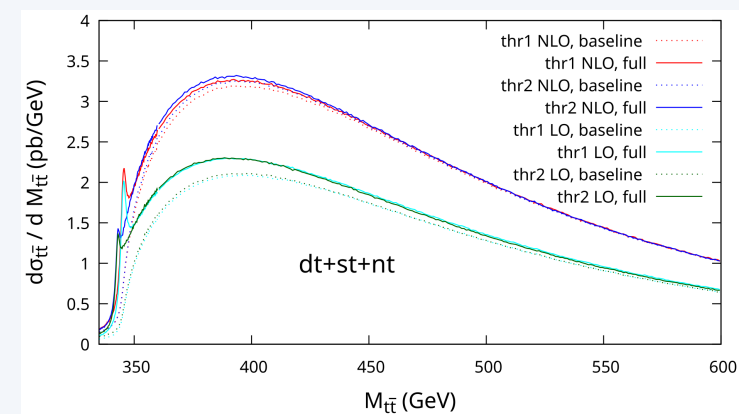
- revive the **non-relativistic Green's function** formalism [Fadin, Khoze '87]
- consistent **width treatment**: no double counting with Breit–Wigner mass smearing



Nason et al. '26

3 POWHEG generators:

- **thr1**: zero width approximation
- **thr2**: phase-space accounting for top off-shellness
- **bb4l**: full off-shell and non-resonant contributions
- Finds enhancement described by first orders of PT



also: Review and systematics evaluation [Garzelli et al. '26]

see also talk by S. Moch

Shower foundations

NLL parton showers

adapted from
[M. van Beekveld,
ATLAS PMG Week '26]

	Alaric [Herren et al. '22]	Apollo [Preuss '24]	FHP [Forshaw, Holguin, Plätzer '20]	PanScales [Dasgupta et al. '20] [van Beekveld et al. '22]
Available for e^+e^-?	NLL	NLL	NLL	Partial NNLL
Available for pp?	NLL (no numerical proof beyond colour singlet)	No	No	NLL (no numerical proof beyond colour singlet)
Available for DIS?	No	No	No	NLL
Recoil distribution	Global for soft, local pT for collinear	As Alaric's soft map, different ord. variable	Global	Local (PanLocal) and global (PanGlobal) variants
Splitting functions at LO	Soft with special ref. direction, +coll remainder	Antenna functions	AP with sharp partitioning	AP with smooth partitioning
Spin correlations	Yes in e^+e^-	No	Yes in e^+e^-	Yes at NLL
Corrections beyond LC	No	No	No	Yes at NLL (NODS)
NLO matching available?	Yes in e^+e^- , using S-MC@NLO at exact colour	Yes in e^+e^- on paper, not yet implemented	Yes in e^+e^-	Yes for CS (dBNLO, P2B or positive weights ESME)
Multi-jet merging?	In e^+e^- : 5 jets (NLO), in pp: 3 jets (LO)	No	No	No
Particle masses?	Yes in e^+e^-	No	No	Yes in e^+e^-
Resonances?	Yes in e^+e^-	No	No	No

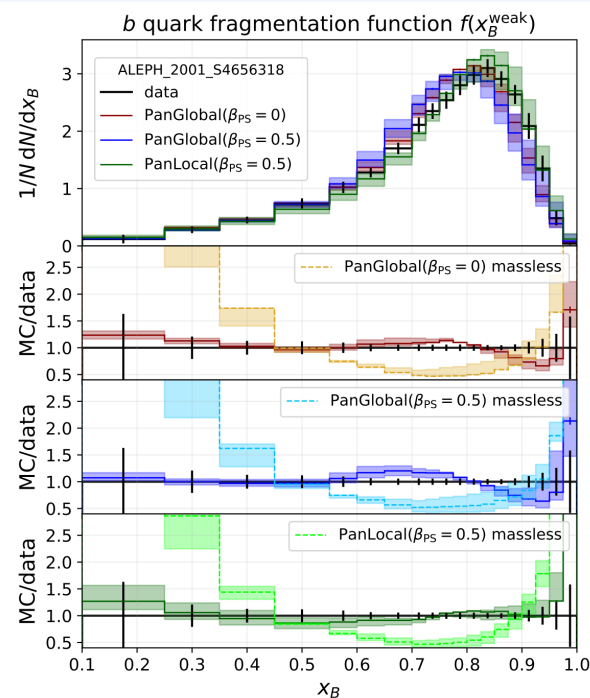
 examples of recent developments on next slide + showers with jet recoils in Pythia [Helliwell, Scyboz, Skands '25]
 + tuning for FHP and PanScale style showers in Herwig

NLL showers: recent developments

PanScales with massive quarks

[van Beekveld et al. '26]

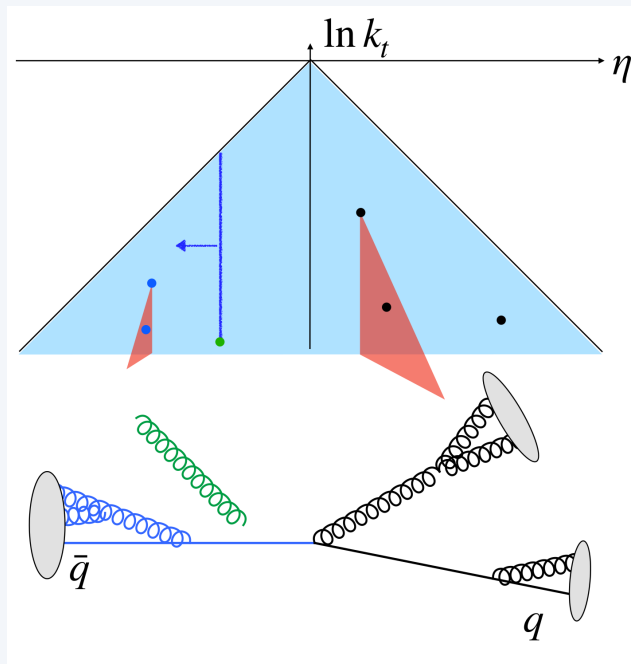
- final state PanScales showers with masses



Showers with jet recoils

[Helliwell, Scyboz, Skands '25]

- Middle ground between local and global recoil

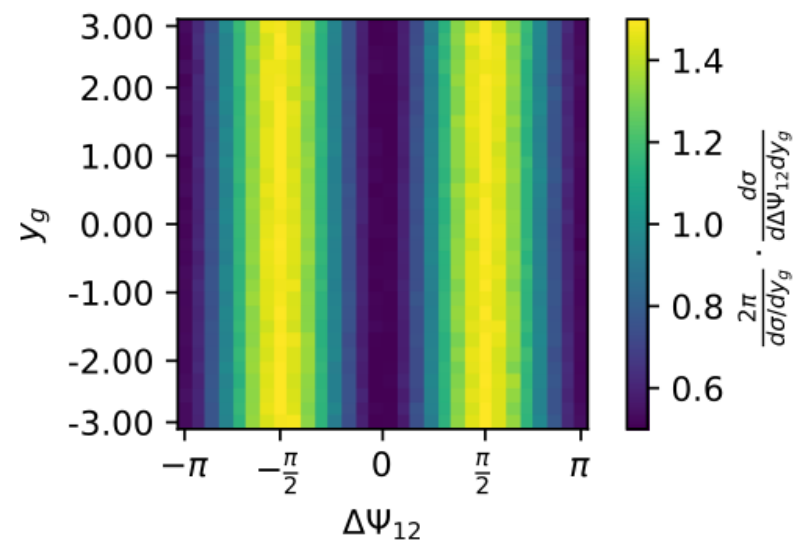


Spin correlations in Alaric

[Höche, Hoppe, DR '25]

[Campbell et al. '25]

- Semi-classical correlations based on scalar + spin split of splitting functions

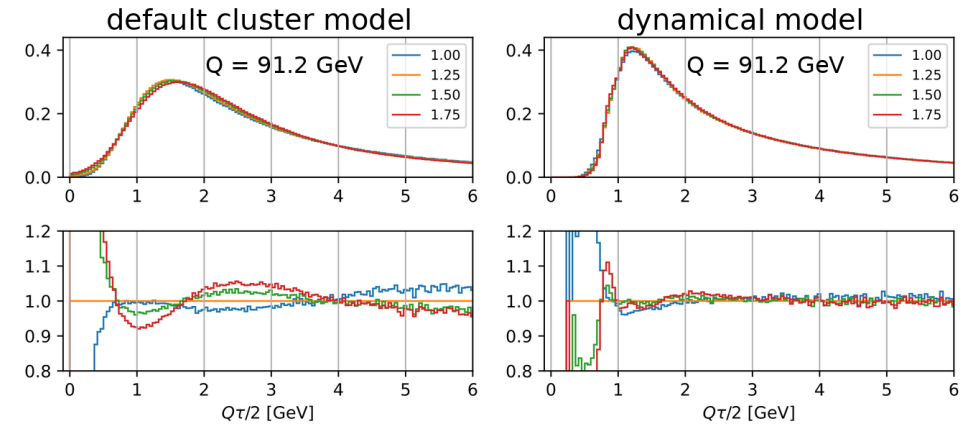


Shower-hadronisation interplay

Shower cutoff as a constraint

[Hoang et al. '24]

- structure of **hadronisation corrections** in principle determined
- shower-cutoff (in)dependence of hadron-level results can be used to **constrain the model**

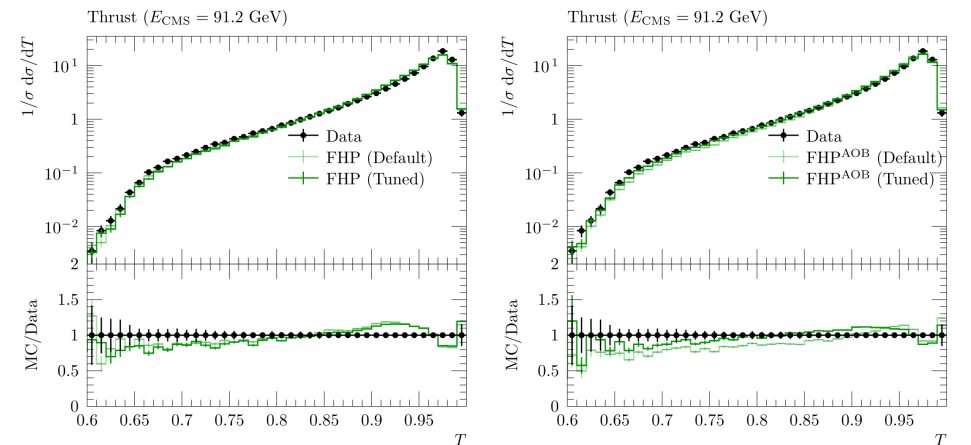


[Hoang et al. '24]

Improved-accuracy showers in Herwig

[Holguin et al. '26]

- several showers in Herwig, traditional: **CS dipole**, **AO**; new NLL showers: **PanGlobal kinematics**, **FHP**
- **different cutoff prescriptions**: own evolution variable or following AO cutoff, gives usually better description after tuning



[Holguin et al. '26]

Showers on **GPU**s [Seymour, Sule '24] [Seymour, Sule '25]

GAPS programme

New ideas on shower accuracy

Shower evolution beyond LO

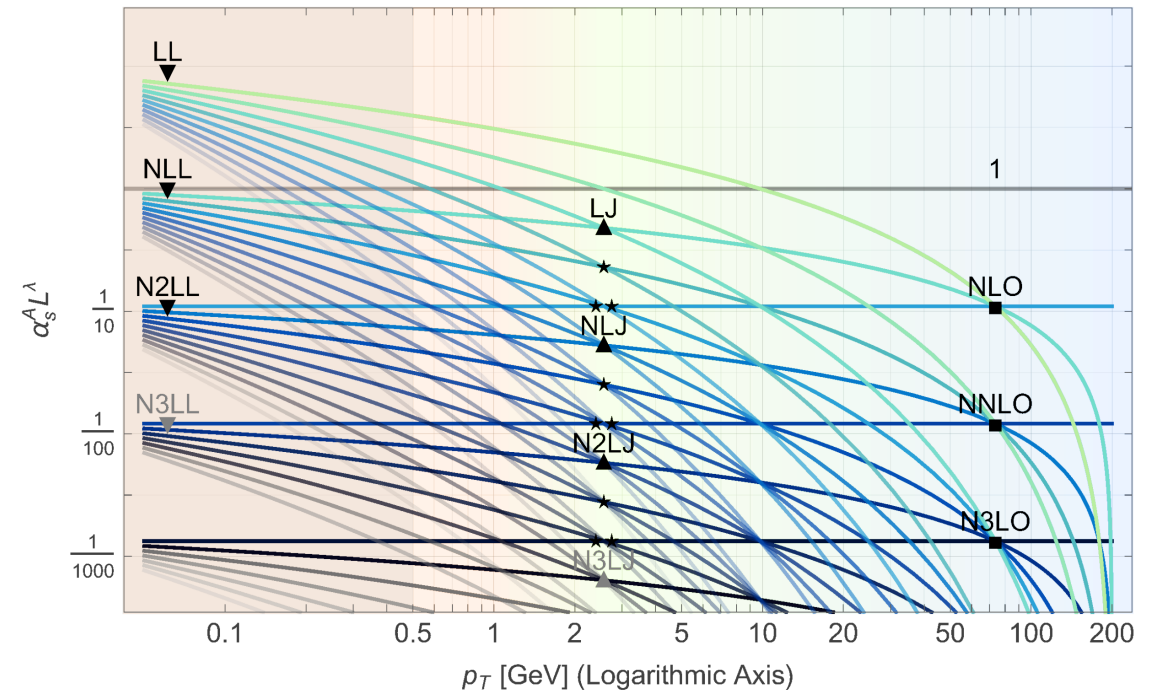
[Nagy, Soper '26]

- DEDUCTOR: shower evolution as a **renormalisation-group equation**
- deriving DEDUCTOR evolution at second order from IR renormalisation

Thinking beyond logarithmic accuracy with Cat's cradle diagrams

[Skands '26]

- between IR and UV extremes: log-enhanced leading contributions to higher log become important, see also e.g. [Höche, Siegert, DR '18]



Cat's cradle diagram illustrating numerical sizes of perturbative contributions [Skands '26]

suggested systematic counting $N^n \text{LJ}$:
terms $\alpha_s^A L^\lambda$ with $n = A + 2(1 - \lambda)/3 - 1$

Summary & Further topics

Colour evolution in parton showers

- non-global logs vs. NGL resummation
[\[Banfi, Dreyer, Monni '21\]](#)
[\[Becher, Schalch, Xu '23\]](#)
[\[Ferrario Ravasio et al. '23\]](#)
- new ideas in amplitude evolution
[\[Forshaw, Plätzer, González '25, '25\]](#)

QED+QCD matched showers

- update POWHEG-BOX DY QED
[\[Chiesa, Del Pio, Piccinini '24\]](#)
- MiNLO for QED corrections
[\[Belloni et al. '26\]](#)
- QCD+EW MC@NLO + interleaved shower
[\[Flower et al. '26, '26\]](#)

see talks by L. Flower and J. Roper

Polarised DIS

- in Herwig
[\[Masouminia, Papaefstathiou, Richardson '26\]](#)
- new POWHEG generator
[\[Borsa, Betz, Jäger '26\]](#)

see talk by I. Borsa

Matching & merging with NLL showers

- Alaric LO & NLO merging
[\[Höche et al. '24 '25\]](#)
- PanScales NLO DY
[\[PanScales '25\]](#)
- Matched FHP shower in colour singlet decay
[\[Holguin et al. '26\]](#)

Summary

- **NNLO matching:** pushing frontier with new processes + ideas for shower inspired schemes
- **NLO:** improved frameworks with positive weight matching, resonance and width aware MC@NLO, top threshold
- **Showers:** improved NLL showers, new ideas for shower-NP interplay, new ways to think about shower accuracy