# Parton Showers

Simon Plätzer Institute of Physics — NAWI, University of Graz Particle Physics — University of Vienna

At the QCD@LHC workshop Freiburg | 7 October 2024

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Synthesis of Enantiopure Sulfoxides by Concurrent Photocatalytic Oxidation and Biocatalytic Reduction

Sarah Bierbaumer, Dr. Luca Schmermund, Alexander List, Dr. Christoph K. Winkler & Dr. Silvia M. Glueck





https://particle.uni-graz.at/en/event-generators-and-resummational









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### Parton Showers (& Hadronization) b) Vorgabe für Publikation von WissenschafterInnen, die den Kooperationen NAWI Graz und BioTechMed-Graz zuzuordnen sind

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## Setting the scene



### $d\sigma \sim L \times d\sigma_H(Q) \times PS(Q \to \mu) \times MPI \times Had(\mu \to \Lambda) \times ...$



## Setting the scene



 $d\sigma \sim L \times d\sigma_H(Q) \times PS(Q \to \mu) \times MPI \times Had(\mu \to \Lambda) \times ...$ 100's of GeV 1-2 GeV few 100's MeV



## Setting the scene

Central for realistic description of the observed complexity.





Description of IR sensitive observables shower and hadronization factored, but intertwined

### Probabilistic algorithms with QCD coherence or large-N limit I <sup>2</sup> qit hutment tt t.it Mmm nt IC y regular<br><u>Ice y regular province</u>

 $\alpha$  paint  $\alpha$   $\alpha$   $\beta$   $\gamma$   $\alpha$   $\beta$ 

Martin Pri Puig 9m

2

Martin Pri Puig 9m

e de la contradición de la contrad<br>En el contradición de la contradici e terminale de la construction de<br>La construction de la construction emission rate no emission probability

 $d\sigma \thicksim L \times d\sigma_H(Q) \times \mathrm{PS}(Q \to \mu) \times \mathrm{MPI} \times \mathrm{Had}(\mu \to \Lambda) \times ...$ 

 $\mu_{\mathfrak{m}}(p_1, p_2, p_{\mathfrak{m}})$  T  $\cdots$  T o T  $\cdots$  T  $\mu_{\mathfrak{m}}(p_1, p_{\mathfrak{m}})$ 

Mat pain putt T T Mu pai<br>T T Mu pain putt T T Mu pain putt T

2

All probabilistic algorithms determine the effect of gluon exchange and virtual corrections by unitarity.  $T(t)$  Texting  $T(t)$  that  $T(t)$  the Times of Times  $T(t)$  that  $T(t)$  correction









$$
dS = \frac{\alpha_s}{2\pi} \frac{d\tilde{q}_i^2}{\tilde{q}_i^2} dz P(z_i) \exp\left(-\int_{\tilde{q}_i^2}^{Q^2} \frac{dq^2}{q^2} \int_{z_{-}(k^2)}^{z_{+}(k^2)} d\xi \frac{dq}{2}\right)
$$

emission rate





Exploit QCD coherence:

Parton branchings order in angle.

Dipole branchings order in transverse momentum.

- Recoil global
- Links to analytic use of coherent branching
- Driven by large-N dipole pattern and colour flows
- Momentum conservation for each emission
- Advantageous for matching & merging

**Herwig 7**

### **Herwig 7, Pythia 8, Sherpa, PanScales, Deductor**





Plethora of approaches to compare — need to go beyond in understanding and controlling shower algorithms.















## Favorite probabilistic algorithms



Driven by QCD coherence

## Main lines of current parton shower research

Shower development is a broad field, fortunately back on the agenda. Hadronziation is not exactly shower development, but enters at a similar level,

Amplitude evolution

Genuine quantum effects: not limited to subleading colour. Hadronization

See Schumann's talk. Always needs to accompany shower development.

Matching/Merging (N)NLL accuracy

Comprehensive, factorized picture and construction of algorithms.

Control and demonstration of perturbative accuracy.



• Factorisation and hadronization.



## The struggle with QED, EW and other interactions







- The absence of a large-N limit forces us to question existing structures
- Accuracy from interleaving with QCD needs to be carefully addressed
- The inner workings and role of coherence is entirely unknown



**Adding CADINGS.**<br>The CHIC CADINGS. Recent examples:

Θ

➤ **VINCIA** is a **sector shower**: **phase space** available for an  $\Theta$  L<sup>V</sup>CHIC/CH, SKan [Verheyen, Skands— '21]

➤ Dipole showers reproduce the soft **QCD radiation participals** number of colour approximation of colour approximation Sectorised QED multipoles and electroweak splittings in VINCIA

Halfway safe ground in the quasi-collinear limit, should be exploring these algorithms. Spin correlations are vital — amplitude evolution will be crucial to build algorithms.

> Multiscale interleaved angular ordering in Herwig

Interactions beyond QCD



### Dark sector showers

QCD-like dark sectors can in principle build on existing QCD showering.<br>
Interactions beyond QCD Hadronization and scale hierarchy can differ significantly: no safe territory.

New in Herwig and the cluster model — more investigations and pheno to follow.







### Dark sector showers

QCD-like dark sectors can in principle build on existing QCD showering.<br>
Interactions beyond QCD Hadronization and scale hierarchy can differ significantly: no safe territory.

[Stafford at PSR '24]

 $A = \frac{1}{2}$  and  $A = \frac{1}{2}$ — wny botner

8 Suchita Kulkarni et al.: Dark Sector Showers and Hadronisation in Herwig 7







 $0'$ GeV enarios force us and <sup>0 Ge</sup>  $\bigcap_{n=1}^{\infty}$  also recent Linis and Di **LEP and** *Z***PP, LAN and DSP ISCENATION**<br>External CONVICTION CONTINUES aligned CD iented nd hadronisation in an unprecedented way. D, EW and BSM scenarios force *kceparios force*  $\theta$  $\overline{\mathcal{O}}$ *R*) for *g* LEP at the *Z* pole is the *Z* pole is a pole in the *Z* pole is a police of the *Z* police of Energy-weighted corprecedenced *wap*. Think of this as BSM4QCD: all of QED, EW and BSM scenarios force us to think about showers and hadronisation in an unprecedented way.

New in Herwig and the cluster model — more investigations and pheno to follow. **Energy-weighted Correlations**





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Description of electroweak effects and BSM scenarios.

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## Accuracy of parton showers



Fragmentation is fine if we get collinear physics right.





### Accuracy of Parton Showers

Global event shapes from coherent branching — for two jets.

 $H(\alpha_s) \times \exp(Lg_1(\alpha_s L)) +$ 



$$
g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + ...
$$

LL — qualitative  $\hbox{NLL}$  — quantitative  $\hbox{NNLL}$  — precision  $\alpha_s L \sim 1$ 

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## Accuracy of Parton Showers

Fragmentation is fine if we get







Issues in dipole showers

Can we push this to NLL<sub>global</sub> / LL<sub>non-global</sub> in one (dipole) algorithm?

Issues in coherent branching LL with dipole showers

 $\alpha_s L \sim 1 \quad \alpha_s N^2 \sim 1$ 



## The quest for NLL precision



(N)NLO with matching<br>
NLL with coherent branching<br>
leaves in direct of the ways

## The quest for NLL precision

Demonstrate NLL accurate evolution:

• PanScales — numerical



 $\alpha_s L \sim 1 \quad \alpha_s N^2 \sim 1$ 



• Apollo — numerical

Can we push this to NLL<sub>global</sub> / LL<sub>non-global</sub> in one (dipole) algorithm?

[aim at improving Herwig 7 dipole shower]

• Deductor — numerical/analytical

UNCI på 1999 Hans Nation mattagered.<br>Fillerrent blöche Krauss Reichelt Schänherri • Sherpa — numerical/analytical

[Herren, Höche, Krauss, Reichelt, Schönherr]

[PanScales — Dasgupta, Monni, Salam, Soyez + ….]

• Forshaw/Holguin/Plätzer — analytical





− ln Q/q(a1,b1)<br>− ln Q/q(a1,b1) 1 ⊥

− ln Q/q(a2,12) 2 ⊥

### Improving Shower Accuracy — Tools needed to compute some observables to NLL accuracy, e.g. thrust. Regardless, it  $i$  is an important incorrectly can spont that if  $A$ shower [10]. Addressing this is the focus of the next section. 3 Improving recoil in dipole showers i<br>I ! <sup>2</sup><sup>π</sup>  $\mathbf{0}$ dφ<sup>2</sup>  $\overline{\phantom{a}}$ e−l e−



Coherence: more generally



derivation. Rather it is inspired by the study of recoil by Bewick et al. [17]. Bewick et

0

q

0

 $\overline{a}$ 

q

[van Bleekveld @ MBI '24]





[Karlberg, Salam, Scyboz, Verheyen — '21]

k angular extent of evolution produce colour factors as ted by coherence.

1

*d*3⌃

=

 $\frac{1}{2}$ 

8*EiEjEk*

*<sup>Q</sup>*<sup>3</sup>

⇣

-(*ij*)*k*)

L,

Ξ  $\overline{a}$ 

✓*<sup>S</sup>* -✓*ij*

 $\overline{a}$ Ξ  $\overline{a}$ 

✓*<sup>L</sup>* -✓*jk*

 $\overline{a}$ 



*J*



### Tolour Correlations (2011.02492)] <sup>c</sup> suppressed error produced by our original dipole shower. Improving Shower Accuracy — Spin & Colour Correlations

**Spirit**  $\epsilon$  $\overline{\phantom{a}}$ 6 illustrate errors that occur in the case of three emis-Spin correlations building on Collins-Knowles algorithm

at the end of this section (see also  $\mathcal{S}$  and  $\$ 

$$
C_{iJ}(\theta_{iq}, \theta_{LJ}) = \left(C_F \delta_i^{(q)} + \frac{C_A}{2} \delta_i^{(g)}\right) \theta(\theta_{iq} < \theta_{LJ})
$$
  
+ 
$$
\left(\frac{C_A}{2} \delta_J^{(g)} + C_F \delta_J^{(g)}\right) \theta_{LJ}^{(q)} > \theta_{LJ}
$$
  
to re  
o  
o  
overon

[Forshaw, Holguin, Plätzer — '21] [Hamilton, Medves, Salam, Scyboz, Soyez — '21] is the part of the sub-branch emitted at the sub-branch emitted at the sub-branch emitted at the largest sub-<br>In the largest at the largest sub-branch emitted at the largest sub-branch emitted at the largest sub-branch e

rection of one of the hemispheres), the matrix elements



[Webster, Richardson - '20]  $s_{\rm t}$ sisti $s_{\rm t}$  the parton and its "parton", see Fig.  $s_{\rm t}$ ure 8. We only need to modify colour factors for glu-to-modify colour factors for glu-to-modify colour factors<br>The glu-to-modify colour factors for glu-to-modify colour factors for glu-to-modify colour factors for glu-to-

### *D***ynamic colour facto** namic colour raccor (gluon), and zero otherwise. We stress that this correction leads to the correct result only because our way of ons which cannot probe the largest angle in the largest angle in the largest angle in the largest angle in the  $\sim$ Dynamic colour factors in dipole showers



TAMING THE ACCURACY OF EVENT GENERATORS  $\mathcal{L}_\mathbf{A}$  and  $\mathcal{L}_\mathbf{A}$  and  $\mathcal{L}_\mathbf{A}$  and  $\mathcal{L}_\mathbf{A}$ 

### NLL accurate for global observables with massive quarks. of the mass of the mass of the mass of the mass of the material parties the material parameter of the material , which shows  $\mathcal{L}$

### Top mass definition from coherent branching. from For show the evolution of partons with space-like virtualities, the evolution variable virtuality of partons with space-like virtuality of  $\sim$

 $m_t^{\text{MC}} =$ 

[Hoang, Plätzer, Samitz — '18]

### Where it (also) matters  $\mathcal{L} = \mathcal{L} \times \mathcal{L}$ where it (also) matters and the next-to-leadingthat are also strongly colour suppressed. We stress however, that whereas angular ordering leads

Coherent branching jet mass including mass effects:

Once again this definition of the evolution variable is a generalization of the analogous FORTRAN Take home message: hadronization and mass scheme comper Take home message: hadronization and mass scheme compensate for shower cutoff dependence.

$$
z(1-z)\tilde{q}^{2} = -m_{\tilde{i}j}^{2} + \frac{m_{i}^{2}}{z} + \frac{m_{j}^{2}}{1-z} - \frac{p_{\perp}^{2}}{z(1-z)}
$$

where  $\left[ \text{G}_{\text{B}} \right]$  is the one-shell mass of particle in the one-shell mass of  $\text{G}_{\text{B}}$  is a by generalizing at by generalizing at by generalizing at by generalizing at both  $\text{G}_{\text{B}}$  is a by generalizing at bo using [Gieseke, Stephens, Webber – '03]



$$
m_t^{\text{pre}} + \Delta_m^{\text{pote}} + \Delta_m^{\text{non-per}}
$$
  

$$
m_t^{\text{pole}} - \frac{2}{3}Q_0 \alpha_s(Q_0) + \mathcal{O}(\alpha_s^2)
$$



## Beyond NLL<sub>global</sub> — more different

### Inclusive emission probability - *C*<sup>2</sup> *<sup>F</sup>* channel <sup>Ξ</sup>*n,*1*,*rad = 1 <sup>−</sup> *<sup>θ</sup>*(*p*<sup>0</sup> *<sup>n</sup>*+1 <sup>−</sup> *<sup>µ</sup>S*)Θ*λ*(*n<sup>i</sup> · <sup>p</sup>n*+1*/p*<sup>0</sup>  $A^{\sigma}$  derives and the contributions to the contribution from the evolution from the real end of  $A$  $\frac{1}{2}$ sions. The exormal then  $\frac{1}{2}$  then  $\frac{1}{2}$  then  $\frac{1}{2}$  is a known with the society  $\frac{1}{2}$ is. UIICOVEI aiguitumis and Dencimiai KS.  $\rightarrow$   $c_i'$   $\rightarrow$ *n* <sup>=</sup> <sup>−</sup>! *i<j* **T***<sup>i</sup>* ◦ **T***† j*  $\sum_{i}$ and accordingly be supplemented by a resolution criterion which we take to be and accordingly by a resolution criterion criterion which we take to be take t <sup>Ξ</sup>*n,*1*,*rad = 1 <sup>−</sup> *<sup>θ</sup>*(*p*<sup>0</sup> *<sup>n</sup>*+1 <sup>−</sup> *<sup>µ</sup>S*)Θ*λ*(*n<sup>i</sup> · <sup>p</sup>n*+1*/p*<sup>0</sup> *<sup>n</sup>*+1*, n<sup>j</sup> · <sup>p</sup>n*+1*/p*<sup>0</sup> and the derivatives analogously give the contributions to the evolutions to the evolution from the real emiss*ci* rithms and har  $c_i'$ *i*  $\sigma$ Structure of second order ingredients and dedicated resummations: uncover algorithms and benchmarks.

[Dasgupta, El-Menoufi — '21]

### mentum fractions to a set of independent variables is explained in the text. The text. The angle *g* is that between in the text. The angle *g* is that between in the text. The angle *g* is the angle *g* is that between i Effective couplings and collinea Effective couplings and collinear fragmentation



nission kernels beyond LO and the soft gluon with the soft gluon with the soft gluon with the cutoff has not y pletely but will likely cancel for observables in which collinear divergences cancel. We will  $\blacksquare$ Kinematic and colour structure of emission kernels beyond LO

 $\mathbf{L} \mathbf{v}_n$ 

results here can also be used to assemble a full evolution using our results [9] and the double **Butting amplitude evolution at the second of del. Ruilding amplitude quolution at the second order** Building amplitude evolution at the second order.



= **F**(1*,*0)

*<sup>n</sup>* ◦ **<sup>R</sup>**(1*,*0)*†*









due to the colour connection in this is enhanced by a factor of *N*2. The diagonal structure

 $d \log(p^2)$ *,*4*/p*2 *,*3)

 $10^{-6}$  $d\log(p^2)$ *,*4*/p*2 *,*3)

 $\bullet$  2  $\rightarrow$  4 branchings important ingred  $(+$  virtual corrections to 2  $\rightarrow$  3)  $i +$  virtual corrections to  $z \rightarrow s$ , we shall general gluon emission process in  $\mathbb{R}$ 

*z*<sup>1</sup> = 1 *z*  $Oq\bar qg$  $\alpha_s$  $2\pi$  $K(z_g) = \frac{V_{q\bar{q}g}}{P}$  $B_{q\bar{q}g}$  $\frac{V}{I}$  $\boldsymbol{B}$ 

Figure 3. The Feynman diagram representing the gluon emission *C*<sup>2</sup> tum fractions to a set of independent variables in the text. In the text. functions reduce (after azimuthal integration for the gluon decay channels) to a product of leading-[Van Beekveld, Dand ... Hifforontial. Halliwell, Karlberg

### **PanScales double s** and splitting functions of the space in the space in the space in the space in  $\mathbf{A}$  $\cap$ rdering [C. Preuss for Vincia  $V$ inc fix ✓<sup>13</sup> = ✓ ⌧ 1, the angle of emission 1 wrt the *final* quark, which shall set the collinearity, and the Nuovo study the Nuovo structure induced angle emission labelled 2, with angle of *∠23 ×* with angle *2*, with angle *z* with angle of *z* with angle *z* with real emission contain poles in  $\mathcal{C}$  which reflect singularities that cancel when we can cancel when we **DESY.**

 $10^{-6}$ 



Effective couplings and the extended the the state of **extending the extended of the extended** of  $\overline{P}$ 

Inclusive emission probability - *C*<sup>2</sup>

## Beyond NLL<sub>global</sub> — more different

*<sup>F</sup>* channel



Results

### **• Momentum mapping**

Towards second-order showers:

- **o** sector showers allow to include dire a simple way
- divide phase space into **strongly-orders and 2, the variable and 2, the variable and 2, the variable** *and 2***, the variable** *and 2***, the variable** *and 2, the variable and 2, the variable and 2, the variable <i>x* **and 2, the v** region energy fraction of the final-state of the final-state of the energy fraction associated to the energy fraction associate
	- **In s.o. region: only single-unresolvent**
- **Example 3.5.** Figlon. Shigh single different gluon. In addition we shall also study the distribution of the distribution we shall also study the distribution of the distribution of the distribution of the distribution of

 $\sum_{\substack{m=1\\ \infty}}^{\infty} 10^{-6}$  integrals with integrals we can rectified the form of the fo

 $z_1 = (1-z)z_p$ , their ingredients. Algorithms are more than the sum of

 $\blacksquare$   $\blacks$ *F F* annel moment of the moment  $\overline{S}$  $\mathbf{r}$  $e$ **monstra**  $\overline{\mathbf{f}}$ <sup>*I*</sup> Demonstrate accuracy for certain  $N_{\rm em}$  B salmald  $N_{\rm em}$ **Partition** allocates the **10** strive for most  $\mathbf{F}$  the option of  $\mathbf{F}$  and subtractive  $\mathbf{F}$  $\blacksquare$  spread soft contributions over  $\blacksquare$ *Si*1*Sl*<sup>1</sup> observables, but strive for most differential/flexible algorithms.

Double emission natural functions 2 July 2022 Finally We discuss the quantities we study the double the double the double the double the double district district **bution in and** *z* is the normalised in the normalised in the normalised in  $\mathbf{R}$  and  $\mathbf{R}$  is the three parton systems. that arises from the triple-collinear splitting of a splitting of a splitting variable  $\bullet$  sector showers allow to include dire  $\blacksquare$  CIEA $\Gamma$  DUT ENCOUMA  $R_0$ lo of dota compa approached and the recoil is clear but encouraging. Role of data comparisons not always

[Dasgupta, El-Menoufi — '21] *z*<sup>3</sup> = *z* Figure 2. The Feynman diagram representing the gluon decay *C<sup>F</sup> C<sup>A</sup>* channel. The mapping of the mo-Effective couplings formulations.  $\int_{a}^{a}$  *M/ay forward* is hard but  $\int_{\mathbb{S}^d} \theta_g$  is that are correlated with the correlations of  $\mathbb{S}^d$ Effective couplings and collinear formulations. Way forward is hard, but possible we need to find systematic



 $\mathcal{A} = \mathcal{A} \cup \mathcal{A}$  have been reporting on similar multi-scale evolution algorithms algorithms are possible evolution algorithms are possible evolution algorithms are possible evolution algorithms are possible evoluti

while this work has been finalized. They only consider leading order evolution though and do not include though and do not include the second though and do not include the second though and do not include the second throug



match. This colour flow is part of the matrix element [⌧ *|*(T*<sup>i</sup> ·* T*l*)(T*<sup>i</sup> ·* T*<sup>j</sup>* )*|*i (cf. Eq.

while this work has been finalized. They only consider leading order evolution though and do not include though and do not include the second order evolution though and do not include the second order evolution that the se

## Main lines of current parton shower research

Shower development is a broad field, fortunately back on the agenda. Hadronziation is not exactly shower development, but enters at a similar level,

Interactions beyond QCD

See Schumann's talk. Always needs to accompany shower development.

Matching/Merging (N)NLL accuracy

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Remaining focus of this talk:

- Perturbative accuracy
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Description of electroweak effects and BSM scenarios.

Genuine quantum effects: not limited to subleading colour. Colour reconnection and hadronization is about subleading-N. So are shower accuracy and interference terms.

Colour factor algorithms Colour ME corrections Full amplitude evolution

[Gustafson] [PanScales '21] [Forshaw, Holguin, Plätzer '21]

[Plätzer, Sjödahl '12, '18] [Höche, Reichelt '20]

Coherent, NLL-accurate dipole showers

Colour-exact real emissions as far as possible Colour-exact real and virtual corrections

[Forshaw, Plätzer + … '13 …] [Nagy, Soper '07 …]



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Colour-exact real emissions as far as possible

### Colour-exact real and virtual corrections

[Forshaw, Plätzer + … '13 …] [Nagy, Soper '07 …]



[Forshaw, Plätzer, De Angelis, Torre, … — '18 … '24]





### The amplitude evolution equation ha amplituda avolution aquation  $\mathcal{M}$  , and the puttracy of the putter  $\mathcal{M}$  and  $\mathcal{M}$  are putter  $\mathcal{M}$  and  $\mathcal{M}$  , and the putting the putting  $\mathcal{M}$  and  $\mathcal{M}$  are putting to  $\mathcal{M}$  , and  $\mathcal{M}$



I in Roylem algorithm at the amplitude Markovian algorithm at the amplitude level:

Different histories in amplitude and conjugate amplitude needed to include interference.



### The amplitude evolution equation ha amplituda avolution aquation



Collinear emissions are emitted symmetrically from the amplitude and conjugate amplitude, such

 $8<sup>8</sup>$ 

as  $\left| \frac{n \times 20} \right| \approx 20$ ,  $\left| \frac{n \times 20} \right| \approx 25600$ ,  $\left| \frac{n \times 20}{n \times 20} \right| \approx 25600$ 

3





### Amplitude evolution at hadron colliders mplitude evolution at hadron collig Mat pain putt <sup>T</sup> <sup>T</sup> <sup>T</sup> Mu pain pm Mat pain putt <sup>T</sup> <sup>T</sup> <sup>T</sup> Mu pain pm







 $M$  and  $M$  pain  $\mathcal{M}$  the putting  $M$  putter  $M$  putting  $M$  putting  $M$  putting  $M$  putting  $M$  putting  $M$ 



Showering of hard process interferences



### responding to the only  $\mathbf{r}$  -  $\mathbf{r}$

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[Chahal, Krauss — '22] clusters and hadrons in *<sup>e</sup>*+*e* ! hadrons events at varying centre-of-mass energies.

Inserting Eq. (1) in Eq. (2), it is ⇢(*q*)=1*<sup>q</sup>/*2 and ⇢(¯*q*) = [Gieseke, Kiebacher, Plätzer, Priedigkeit — in progress] Figure: Thrust *<sup>T</sup> >* <sup>0</sup>*.*8, ~*p*<sup>1</sup> *· <sup>p</sup>*~<sup>2</sup> *>* 0 and *<sup>z</sup>* = p*<sup>s</sup>* [Seidl et al. 2017b]

> $D(VM)$   $\downarrow$   $\uparrow$   $\rho(VM)$  $T_{q \rightarrow h + q'}$  $\overline{q}$ H  $T_{\overline{q}\rightarrow H+\overline{q}'}$  $\cdot |\rho(q,\overline{q})|$  $q'$  $\overline{\mathbf{q}}'$

[Kerbizi, Lönnblad, Martin — '24]

### Hadronization in general purpose event generators **Preliminary: New Cluster Fission Kinematics applied**In Fig. 1 we exhibit the characteristic two distributions that characterise this initial step of the cluster fragment tation model, namely, firstly, the distribution of primary cluster masses in the left panel, and secondly the right panel. The right panel of the right panel. They have been obtained after the CSS have been o **New Cluster Fission Kinematics New Cluster Decay Kinematics**





d2*s*/d*z*d



tuned values of the parameters are given in Appendix B.

<sup>2</sup> <sup>2</sup>(*q*<sup>1</sup> *· <sup>q</sup>*2)(*<sup>q</sup> · <sup>q</sup>*¯)+[*q*<sup>1</sup> *·* (*<sup>q</sup> <sup>q</sup>*¯)][*q*<sup>2</sup> *·* (*<sup>q</sup> <sup>q</sup>*¯)]







[Bellm, Lönnblad, Plätzer, Prestel, Samitz, Siodmok, Hoang — Les Houches 2017]





## Why we should worry about PS x Hadronization



### A factorised approach





Shower cutoff has central role as factorisation scale:

- Shower/hadronization constrained by renormalisation group
- Formulated in amplitude level evolution, contains event generators in large-N limit.







### Systematic construction of amplitude evolution algorithms. an infrared cuto↵ scale *µS*, shall be our starting point. We will devise re-definitions (or observed particles in the systematic construction of amplitude evolution algorithms.

in unresolved regions

Re-arrange to resum IR enhancements

$$
\sigma = \sum_{n,m} \int \int \text{Tr}_n \left[ \mathbf{M}_n \mathbf{U}_{nm} \right] \mathrm{d}\phi_m u(\phi_m)
$$

### A factorised approach fragmentation function, or a completely exclusive hadronization model), subject to a given coppi odci i shall be based on events of finite algorithm, if it shall be based on events of  $\frac{1}{100}$



Subtract IR divergencies 
$$
U_n = \mathcal{X}_n [\mathbf{S}(\mu_S), \mu_S]
$$
  
\nin unresolved regions  
\n
$$
\sigma = \sum_n \alpha_S^n \int \text{Tr} [\mathbf{A}_n(\mu_S) \mathbf{S}_n(\mu_S)] d\phi_n
$$
\nRe-arrange to resum  
\nIR enhancements  $\mathbf{M}_n Z_g^n = \mathcal{Z}_n [\mathbf{A}(\mu_S), \mu_S]$ 





necessarily involves an infrared resolution. The presence of this resolution, *e.g.* through





## A factorised approach

[Hoang, Jin, Plätzer, Samitz — '24] [Gieseke, Kiebacher, Plätzer, Priedigkeit — in progr







 $[Kiebacher @ PSR '24]$ 







**Hadronization From Colour Evolution** Leads to constructive prescription for "high energy" end of hadronization.

First steps demonstrated:

Lower energy dynamics in the model not sensitive to cutoff anymore.

shower IR cutoff

## A factorised approach

[Hoang, Jin, Plätzer, Samitz — '24] [Gieseke, Kiebacher, Plätzer, Priedigkeit — in progr



# **Shower Cut-off** is a factorization scale (see also



from amplitude evolution structures: Colour reconnection dynamics implied



 $\begin{array}{r} \text{[Kiebacher} \text{\textcircled{O}} \text{PSR '24} \end{array}$ 





**Hadronization From Colour Evolution** Leads to constructive prescription for "high energy" end of hadronization.

[Gieseke, Kirchgaesser, Plätzer, Siodmok — '17, '18] **Fig. 7** The transverse momentum spectra for <sup>π</sup><sup>+</sup> <sup>+</sup> <sup>π</sup><sup>−</sup> and p + ¯p as measured by ALICE at <sup>√</sup>*<sup>s</sup>* <sup>=</sup> 7 TeV [25] in the very central rapidity region |*y*| *<* 0*.*5



## Summary

Parton showers are central to event generators.

I emphasise that we study shower *algorithms* rather than shower *models* — predict QCD effects in a hierarchy of strongly ordered energy scales.

We can, and need, to assess their accuracy and strive for underlying, well-defined, construction principles.

Infrared sensitive observables are of course the prime test bed — matching will do remaining aspects for jet observables. Hadronization can not be looked at in isolation but is intertwined with parton showering.

Amplitude evolution provides us with a new paradigm which we can use to construct parton showers, as a dedicated resummation tools and eventually to study the structure of amplitudes using simulation.

 $d\sigma \sim L \times d\sigma_H(Q) \times PS(Q \to \mu) \times MPI \times Had(\mu \to \Lambda) \times ...$ 







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