Daniel Reichelt, 20 January 2024

based on

Herren, Höche, Krauss, DR, Schönherr JHEP 10 (2023) 091 [arXiv[:2208.06057\]](https://arxiv.org/abs/2208.06057) Höche, Krauss, DR [arXiv:[2404.14360\]](https://arxiv.org/abs/2404.14360)

The Alaric parton shower

Funded by the European Union

Colliders for theorists ERS ION GNE

- Event simulation factorised into
	- Hard Process
	- Parton Shower Crucial for precision Collider Physics
	- PDF/Underlying event ● Parton Shower
	- Hadronisation
	- QED radiation ● Hadron Decays
	- Hadron Decays

QCD in the soft limit

• factorisation in the soft limit ('Eikonal')

integrate over triangle in "Lund plane"

Relation to structure of (NLL) resummation

• Additional components: collinear terms form DGLAP splitting kernels, running

- coupling and CMW scheme for α_{s} evolution \rightarrow relevant for single emission only
- Simple event shape:

Simple event shape:
$$
\Sigma(v) = \int d\Phi_n e^{-R(v)} \mathcal{F}(v) \sim \exp(Lg_1(\alpha_s L) + g_1(\alpha_s L))
$$

\n $L \equiv \ln 1/v$
\n $R(v) = \int d\Phi_{+1} \frac{d\sigma_{+1}}{d\Phi_{+1}} \Theta(V(\Phi_{+1}) - v)$
\n $g_i \equiv \sum_k \alpha_s^k L^k$

$$
\mathcal{F}(v) = \lim_{\epsilon \to 0} \epsilon^R \sum_m \int d\Phi_{+1} \frac{d\sigma_{+1}}{d\Phi_{+1}} \Theta
$$

$$
F(\tau) = \frac{\exp(-\gamma_E R')}{\Gamma(1 + R')}
$$

For example thrust:

• Multiple emissions expressed as

Parton showers - Cliff notes version

- no-emission probability (sudakov factor)
- Main ingredients to a shower:
	- 1. splitting kernels $P(z)$ captures soft and collinear limits of matrix elements
	- 2. fill phase space ordered in evolution variable $(k_1, \theta, q^2, \ldots)$, definition of t, z away from exact limit (here all showers $k_{\!t}$ ordered) ^{particles} k_{t} , θ , q^{2} \ldots), definition of t, z
	- 3. generate new final state after emission according to recoil scheme

= 1 E_i^2 *j* $1 - \cos \theta_{ik}$ $(1 - \cos \theta_{ij})(1 - \cos \theta_{jk})$ ≡ $W_{ik,j}$ E_i^2 $p_i p_k$ 1 $1 - \cos \theta_{ik}$ $W_{ik,i}$ $(n_i p_i)(p_i p_i)$ $E_i^2 (1 - \cos \theta_i)(1 - \cos \theta_i)$ E_i^2 $\ell = \ell^2$ ℓ^2 ℓ^2 is the positive contribution, such that the average radiation $E_i^2(1-\cos\theta_{ii})(1-\cos\theta_{ik})$ E_i^2

split into *ij* and *kj* collinear terms [Marchesini, Webber '88] double-counting problem, which can be solved by following the technique of [21]. In this approach, *Wik,j* is written is a parton-showled include implementation leads to soft double counting need to \mathcal{C}

• e.g. Angular ordered shower, downside: problems with NGLs \bullet eq. Angular ordered shower downside: problems with NGI s that it may be it may be it may be it may be it with a strict positivity.

Metion 2[.] follow restani Seymour '971 posed in the following compiled subtraction substantial substantial method compiled with a new algorithm for m
The mapping with a new algorithm for many algorithm for many substantial with a new algorithm for many substant \overline{r} $W_{ik,j} = \bar{W}^i_{ik,j} + \bar{W}^k_{ki,j} \ , \qquad \text{where} \qquad \bar{W}^i_{ik,j}$ ing partons. The extension of this method to soft evolution at next-to-leading order requires the removal of overlap Ω_{in} \vdots Ω_{in} $f \circ \text{H}$ and $f \circ \text{H}$ Option 2: follow [Catani, Seymour '97] *where*

between the explicitly included higher-order corrections in the corrections in the potential ϵ • Iuli phase space coverage, splitting fur Note related ideas in [Forshaw, Holguin, Plätzer '20] • full phase space coverage, splitting functions remain positive definite

$$
W_{ik,j} = \tilde{W}_{ik,j}^i + \tilde{W}_{ki,j}^k, \qquad \text{where} \qquad \tilde{W}_{ik,j}^i = \frac{1}{2} \left(\frac{1 - \cos \theta_{ik}}{(1 - \cos \theta_{ij})(1 - \cos \theta_{jk})} + \frac{1}{1 - \cos \theta_{ij}} - \frac{1}{1 - \cos \theta_{jk}} \right)
$$

$$
\bar{W}_{ik,j}^i = \frac{1 - \cos \theta_{ik}}{(1 - \cos \theta_{ij})(2 - \cos \theta_{ij} - \cos \theta_{jk})}
$$

Alaric Kinematics - splitting vs. radiation kinematics

• Before splitting: • After splitting:

- FIG. 2. Sketch of the splitting wines in final-state evolution. See the main text for details. Note that the u
The unlast form the unlast form the unlast form of the unlast form of the unlast form of the unlast form of th and spectator and spectator • traditional dipole scheme: share transverse momentum recoil between splitter
	- $g \rightarrow q\bar{q}$ splitting (at least naively)
- disadvantage: significant impact on emitter kinematics possible, only *y* y *pip^j pi<i>pi***_{***z***}** $\frac{1}{2}$ *****p* $\frac{1}{2}$ *p* $\frac{1}{2}$ *p* $\frac{1}{2}$ *p* $\frac{1}{2}$ \frac applicable to purely collinear splitting functions (see later)

^pi^K ⁺ *^pj^K ,* (24)

B. Spilling kine, Soon • advantage: treat both particles symmetric, seems like a natural choice for e.g.

• Before splitting: • After splitting:

Collinear Splitting Functions fraction *z* of parton *i* with respect to the mother parton, (*ij*), and on the helicities [84–89]. These splitting functions can be derived using the following Sudakov parametrization of the momenta of the splitting where the notation *i* indicates that parton *i* is removed from the original amplitude, and where (*ij*) is the progenitor **Collinear spiltting Functions Collinear Splitting Eunetians** squared scalar emission vertices alone. **µµµ | Car Ophicmiy | and locrons**
alculate for example $q \rightarrow q\bar{q}$

• Calculate for example $g \rightarrow q\bar{q}$ • Calculate for example $g \to q\bar{q}$ assume Sudakov decomposition like

 $d^{\mu\nu} ($ $\frac{1}{2}$ $p(p,n) = -g^{\mu\nu} + \frac{p^{\mu\nu}-p^{\mu\nu}}{pn}$ p olarisation tensor:
iii/(2000) and $p^{\mu}n^{\nu} + p^{\nu}n^{\mu}$ *p*^{*i*} *b*^{*n*} *b*^{*i*} *d*^{*n*} *<i>n d*^{*n*} *i*^{*n*} *d*^{*n*} *i*^{*n*} *d*^{*n*} *i*^{*n*} *d*^{*n*} *i*^{*n*} *d*^{*n*} *i*^{*n*} *i*^{*n*} *d*^{*n*} *i*^{*n*} *d <i>n*^{*n*} *i*^{*n*} *d i*^{*n*} *i*^{*n*} *d <i>n*^{*n*} $a^{r^{r}}(p,n) = -g^{r^{r}} + \frac{r^{r^{r}}}{p^{r}}$ \blacksquare Polarisation tensor: $q^{\mu} n^{\nu} + n^{\nu} n^{\mu}$ $d^{\mu\nu}(p,n) = -g^{\mu\nu} + \frac{p^\mu n^\nu + p^\nu n^\mu}{2\pi}$ or: **i**
177 $d^{\mu\nu}(p,n) = -g^{\mu\nu} + \frac{p^{\mu}n^{\nu} + p^{\nu}n^{\mu}}{pn}$ polarisation tensor:

 $p \sim 10^{4}$ $p = e^{-\mu\nu} + 4z \cdot z \cdot \frac{k' \perp k' \perp}{\perp}$ $\mathcal{F}_{\mathcal{A}}$ *^g^µ*⌫ + 4*ziz^j* $\int d\vec{r}$ $\int d\vec{r}$ and k^{μ} k^{ν} expressions are obtained by projecting the *O*($\int d\vec{r}$ polarization sum in a physical gauge k_{\perp}^2 of the underlying Born matrix element and the relationships born matrix element and the relationships born matrix element and the relationships born matrix element and the r *k*2 *^t* = 2*pip^j ziz^j* , derived from Eq. (2), result in the familiar expressions $\rightarrow T_R$ $- g^{\mu\nu} + 4z_i z_j \frac{r_{\perp}r_{\perp}}{l^2}$ $\sqrt{ }$ $-g^{\mu\nu} + 4z_i z_j$ k_{\perp}^{μ} $\frac{\mu}{k}$ k_{\perp}^{2} \perp $\overline{1}$

 \bar{n}) $\text{Tr}[\psi_i \gamma^\rho \psi_i \gamma^\sigma] d^\nu_\sigma(p_i;\bar{n})$ for discontinuity of the gluon propagator on the physical degree of σ (region field) in σ $P^{\mu\nu}_{a-1}$ θ $p_j(p_i,p_j) = \frac{\pm n}{2n^2} \, d^\mu_{\ \rho}$ $\int p_{ij}, \bar{n} \rangle \text{Tr}[\,\not\!{p}_i \gamma^{\rho} \not\!{p}_j \gamma^{\sigma} \,] d^{\nu}_{\;\sigma}(p_{ij},\bar{n}) \rangle$ $P_{q}^{\mu\nu}$ *^g*!*^q*(*pi, p^j*) = *^T^R* $2p_i^2$ ij $d^{\mu}_{\ \rho}(p_{ij}, \bar{n}) \text{Tr}[\not\!{p}_i \gamma^{\rho} \not\!{p}_j \gamma^{\sigma}] d^{\nu}_{\ \sigma}(p_{ij}, \bar{n})$ $T_{\rm B}$ $P^{\mu\nu}_{g\rightarrow q}(p_i,p_j) = \frac{-\pi}{2\pi^2}\, d^\mu_{\,\,\rho}(p_{ij},\bar{n}) \text{Tr}[\,\rlap/p_i\gamma^\rho\rlap/p_j\gamma^\sigma\,]d^\nu_{\,\,\sigma}(p_{ij},\bar{n})\,.$

• evaluate in collinear limit: $f \rightarrow T_R$ | $- g^{\mu\nu} + 4z_i z_j - \frac{1}{2}$ | e *valuate g* valuate in collinear limit: 2*p*² • evaluate in collinear limit: g ollinear limit: $\longrightarrow T_R$

assume Sudakov decomposition like

Collinear Splitting Functions where the notation *i* indicates that parton *i* is removed from the original amplitude, and where (*ij*) is the progenitor **Collinear Splitting Functions** fraction *z* of parton *i* with respect to the mother parton, (*ij*), and on the helicities [84–89]. We define the diright splitting functions of Eqs. (4) and the purely collinear Splitting functions of Eqs. (4) \sim splitting function, *P*k(*pi, p^j*). Using the known spin dependence of the quark splitting function, we obtain the following 1*,...,i*(*ij*)*,...,j\,...,n* 2*pip^j* ¹*,...,i*(*ij*)*,...,j\,...,n*^E *n*1 where the notation is removed from the original and where α is the progenitor α is the progenitor α applications we will define *K*˜ as the sum of all final-state momenta (in the case of final-state branchings also including the momentum of the splitting particle). Together, the momenta *K*˜ and ˜*pⁱ* define the reference frame of the splitting. The momentum of the color spectator, ˜*pk*, defines an additional direction, and provides the reference for the azimuthal *y* onnear opiitung *.* (16) \blacksquare

dos fraction *z* of parton *i* with respect to the mother parton, (*ij*), and on the helicities [84–89]. is constructed with transverse momentum component

$$
p_i^{\mu} = z_i \hat{p}_{ij}^{\mu} + \frac{-k_t^2}{z_i 2p_{ij} \bar{n}} \bar{n}^{\mu} + k_t^{\mu} ,
$$
\n
$$
p_j^{\mu} = z_j \hat{p}_{ij}^{\mu} + \frac{-k_t^2}{z_j 2p_{ij} \bar{n}} \bar{n}^{\mu} - k_t^{\mu}
$$
\n
$$
P_{gg}^{(F)}(p_i, p_j, \bar{n}) =
$$

<u>act</u>ı *pin*¯ *p*_{ij}_n and *z*^{*j*} \tilde{a} = *n*² \tilde{b} = *n*² \tilde{b} = *n*² \tilde{b} = *n*² \tilde{b} = *n*² \tilde{c} = *n*² $\begin{array}{c|c|c|c} \hline \multicolumn{1}{c|}{\text{Partial shown}} & P_{gq\,||}^{(\mathrm{F})}(p_i) \end{array}$ $\int p_i = (1-z)\,\tilde{p}_i + v(\tilde{K} - (1-z+2\kappa)\,\tilde{p}_i) - k_1$, limately, "proper" $f(x) = \frac{f(x)}{x} + \frac{f(x)}{x} + \frac{f(x)}{x} + \frac{f(x)}{x} + \frac{f(x)}{x} + \frac{f(x)}{x}$ $p_{\text{max}} = K - v(K - (1 - z + 2\kappa)p_i) + k_{\perp},$ z and z , k_{\perp}^2 *P ^µ*⌫ *gq* (*pi, p^j , n*¯) = *T^R* $\overline{}$ *g*^{*i*}*y* + 4*z*^{*i*}*j*^{*y*}_{*j*} + 4*z*^{*i*}_{*j*} + 4*z*^{*i*} $\frac{1}{\sqrt{2}}$ P^J 1 - $v(1 +$ $\kappa)$ $\hat{p}_{\bm{i}\cancel{.}}$ *zj* ◆ $v(1 - z + \kappa)$ *P ^µ*⌫ (F) $p_i = z\,p_i$, and \overline{z} $p_j = (1-z)\tilde{p}_i + v(\tilde{K} - (1-z+2\kappa)\tilde{p}_i) - k_\perp,$ Ultimately, "proper" $K = \tilde{K} - v(\tilde{K} - (1 - z + 2\kappa)\tilde{p}_i) + k_\perp,$ Crossing parton *i* into the initial state, we obtain the following collinear factorization formula $1 - v(1 - z + \kappa)^{-3}$
 $(1 - z)(1 - z) = uv$ $\frac{\partial}{\partial x} \hat{p}_i$ $\frac{1}{(1-z)(1-z)}$, $\frac{1}{z}$, \cdot α Equation (2) implies that we can compute the light-cone momentum fractions, *zⁱ* and *z^j* as $\sqrt{1}$ $\sqrt{1}$ $\sqrt{2}$ and $\sqrt{2}$ for the discontinuity of $\frac{z}{z}$ and $\frac{k_1^2}{z}$ $p_i = \frac{p_i}{1 - y(1 - z + \kappa)} p_{ij} + \frac{1}{1 - y(1 - z + \kappa)} \sqrt[n]{1 - \kappa} \sqrt[n]{\sqrt[n]{\kappa} \sqrt[k]{\kappa}}$ $\int p_j$ *t* $\frac{1}{\sqrt{1-\frac{1}{2}}}$ Γ actual shower kinematics Γ ^{*rgq* || $(P_i, p_j, n$} $p_i = z \tilde{p}_i$, $(K - (1 - z + 2\kappa)\tilde{p}_i)$ $- k_{\perp}$, $+ k_{\perp}$, *actual shower kinematics:* $p_i = z\,p_i \;,$ $f(x) = (1-z)\tilde{p}_i + v(\tilde{K} - (1-z+2\kappa)\tilde{p}_i) - k_\perp,$ [| ultimately, "p $\begin{array}{c|c|c|c|c|c} \n & F & \tilde{K} & \tilde{K} & (1-z+2\kappa)\,\tilde{n}\end{array}$ + k $p_i =$ *z* $1 - v(1 - z + \kappa)$ \hat{p}_{ij} + *z* $1 - v(1 - z + \kappa)$ $p_j =$ $\frac{(1-z)(1-v)-v\kappa}{u}$ $\frac{1 - \nu(1 - z + \kappa)}{1 - \nu(1 - z + \kappa)} \hat{p}_0$ $ij - \frac{z}{1 - \eta(1 - z)}$ $1 - v(1 - z + \kappa)$ *pⁱ* = \mathbf{p} *zⁱ* =

assume Sudakov decomposition like	derivation of splitting functions leads to:			
$p_i^{\mu} = z_i \hat{p}_{ij}^{\mu} + \frac{-k_i^2}{z_i 2p_{ij} \bar{n}} \bar{n}^{\mu} + k_i^{\mu}$,	$P_{qq}^{(\Gamma)}[p_i, p_j, \bar{n}] = C_F (1 - \varepsilon)(1 - z_i)$			
$p_j^{\mu} = z_j \hat{p}_{ij}^{\mu} + \frac{-k_i^2}{z_j 2p_{ij} \bar{n}} \bar{n}^{\mu} - k_i^{\mu}$	$P_{gg}^{(\Gamma)}[p_i, p_j, \bar{n}] = 2C_A z_i z_j$,			
actual shower kinematics:	$p_{gq}^{(\Gamma)}[p_i, p_j, \bar{n}] = T_R \left[1 - \frac{2 z_i z_j}{1 - \varepsilon}\right]$,			
$p_i = z \bar{p}_i$,	$p_j = (1 - z) \bar{p}_i + v(\tilde{K} - (1 - z + 2\kappa) \bar{p}_i) + k_\perp$,	$\mu_i = \bar{K} - v(\tilde{K} - (1 - z + 2\kappa) \bar{p}_i) + k_\perp$,	$p_i = \frac{z}{1 - v(1 - z + \kappa)} \hat{p}_{ij} + \frac{z}{1 - v(1 - z + \kappa)} k_\perp + \mathcal{O}\left(\frac{k_\perp^2}{2\tilde{p}_i \tilde{K}}\right)$,	$z_i = \frac{z}{1 - v(1 - z + \kappa)}$,
$p_j = \frac{(1 - z)(1 - v) - v\kappa}{1 - v(1 - z + \kappa)} \hat{p}_{ij} - \frac{z}{1 - v(1 - z + \kappa)} k_\perp + \mathcal{O}\left(\frac{k_\perp^2}{2\tilde{p}_i \tilde{K}}\right)$	$z_j = 1 - \frac{z}{1 - v(1 - z + \kappa)}$			
$p_j = \frac{(1 - z)(1 - v) - v\kappa}{1 - v(1 - z + \kappa)}$				

 \sim

Towards subleading effects for lepton colliders

- same variations available for lepton colliders (as far as they are applicable)
- example here: EEC from $q\bar{q}$ final state at the Z pole
- systematic variations not captured by e.g. scale variations
	- additional uncertainty
	- kinematics enter splitting functions, hope for systematic reduction at higher orders

New Parton Showers - NLL accuracy • typical claim based on accuracy of splitting

- functions etc.
	- parton showers $∼$ NLL accurate if CMW scheme for strong coupling is used
- observation in [Dasgupta, Dreyer, Hamilton, Monni, Salam '18] (PanScales collaboration):
	- subtleties arise in distribution of recoil for subsequent emissions \Rightarrow phase space where accuracy is spoiled if soft gluon absorbs recoil
	- + in colour assignment
	- also: set of tests for shower accuracy [Dasgupta, Dreyer, Hamilton, Monni, Salam '20]

New Parton Showers - NLL accuracy

- Several solutions/re-evaluations of parton shower concepts:
- [Dasgupta, Dreyer, Hamilton,Monni, Salam, Soyez '20], [vanBeekveld, Ferrario Ravasio, Hamilton, Salam, Soto-Ontoso,Soyez '22]
	- partitioning of splitting functions and appropriate choice of evolution variable can lead to NLL accurate shower for local and global recoil strategies
- [Forshaw, Holguin, Plätzer '20]
	- Connections between angular ordered and dipole showers
- [Nagy, Soper '11]
	- local transverse, global longitudinal recoil
- [Herren, Krauss, DR, Schönherr, Höche '22]
	- global recoil, enables analytic comparison to resummation and proof of NLL accuracy
- [Preuss '24]
	- global recoil in antenna shower Vinca

Compare: resummation e.g. in CAESAR

- factorisation of matrix elements in soft collinear limit well known
- how to extract NLL observable independent (i.e. without additional information)?
- method from [Banfi, Salam, Zanderighi '05]: need explicit implementation of soft-collinear limit*:

$$
k_t^{\rho} = k_t \rho
$$

\n
$$
\eta^{\rho} = \eta - \xi \ln \rho
$$

\nand assume
\n
$$
V(k_i^{\rho}) = \rho V(k_i)
$$
 in the image, and the
\n
$$
V(k_i^{\rho}) = \rho V(k_i)
$$
 in the
\n
$$
V(k_i^{\rho}) = \rho V(k_i)
$$

Effect of recoil on accuracy ct of recoil on accuracy

- question: do recoil effects indeed vanish in soft limit (i.e. $\rho\rightarrow 0$)?* [Dasgupta,Dreyer,Hamilton,Monni,Salam '18]
- consider situation where we first emit \tilde{p}_{ij} from p_a , p_b , then emit p_j , $\tilde{p}_{ij} \rightarrow p_j, p_j$ Here we have $\sum_{i=1}^{\infty}$ is a from n with $\sum_{i=1}^{\infty}$ and n and n
- transverse momentum of p_i will be as • but, relevant limit is $k^{\dot{l}}_t$ *t* $\sim k_t^{ij} + k_t^j \rightarrow k_t^{ij}$ *kj t ki t* $\rightarrow 0$ between *z*, *y* and *k*² T: Δk_t^i *t* → ρk_{t}^{j} *t*

simultaneous rescaling *l*
be vant limit is
additurent in the post in *ki t*

ρki

t

Alaric - Numerical validation I

• Limit $\alpha_{\rm s} \rightarrow 0$ with $\lambda = \alpha_{\rm s}L = \text{const.}$ of

if shower reproduces LL, NLL logs \rightarrow 1

• Observable: jet resolution y_{23} in Cambridge jet measure, $\mathscr{F}=1\to$ only largest emission matters, check that additional shower emissions vanish

1

$$
\frac{\Sigma \text{Shower}}{\Sigma \text{NLL}} \sim \exp\left(f_{\text{Shower}}^{LL} - Lg_1(\alpha_s^n L^n)\right)
$$

$$
\times \exp\left(f_{\text{Shower}}^{NLL} - g_2(\alpha_s^n L^n)\right)
$$

$$
\times \exp\left(\mathcal{O}(\alpha_s^{n+1} L^n)\right)
$$

Alaric - Numerical validation II

Sherpa MC

 $\Sigma(\alpha_s \ln FC_1)$

PS / NLL 0.98 even for standard 1.02 PS / NLL \rm{PS} / \rm{NI} 1.0 showers 0.98 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0 Sherpa MC ι $FC_1/2)$ 1 $\mathcal{F} = \frac{\exp(-\gamma_E R')}{\Gamma(1+R')}$ 10^{-1} $\Gamma(1+R')$

 $\alpha_s = 0.0025$

1

 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 108 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{3} 10^{-2} 10^{-1}

0.98

1.0

1.02

PS / NLL

0.98

1.0

1.02

PS / NLL

0.98

1.0

1.02

PS / NLL

 $\overline{\Xi}$

1.0

1.02

PS / NLL

PS / NLL

PS / NLL

PS / NLL

kt

 $\alpha_s = 0.005$

virtuality

 α **s** \in 0.01

 $\mathscr{F} =$

 $= 0.02$

 $\mathcal{F} = \frac{\exp(-\gamma_E R')}{\Gamma(1+R')}$ $\Gamma(1+R')$

 $a \n\bigcap_{i=1}^n a_i = 0$

 $\sum_{\alpha=1}^{\infty}$ the thrust

Alaric - Numerical validation III

4 NNLL needed to • Conclusion from PanScales studies: describe even simple observables.

• Appears to be in contrast with small effects found so far in implementing higher order splitting functions (though not in complete NNLL framework yet) [Höche, Prestel '17], [Dulat, Höche, Prestel '18], [Gellersen, Höche, Prestel] n_{\parallel} NLO LO ة
Hi 1 \mathbf{P} tras *s*/d

Achieved by multiplicative matching of NLO splitting kernels + correction terms capturing effect of inclusive gluon

shows the ratios of the NNLL (NLL) shower variants to data.

Summary

• partial fractioning of eikonal leading to positive splitting functions filling full phase space • global kinematics for soft splitting functions, guarantees NLL and analytic tracking of

- Alaric parton shower
	-
	- accuracy
- new developments:
	- CKKW merging
	- systematic variations of NLL ambiguities
- future
	- MC@NLO matching on the way (enabling NLL' accuracy in the soft limit)
	- higher order splitting functions with Dire technique + new kinematics
	- spin correlations to complete radiation pattern