Angeles, De Angelis, Forshaw, Plätzer, Seymour – JHEP 05 (2018) 044
Gieseke, Kirchgaesser, Plätzer, Siodmok – arXiv:1808.06770
De Angelis, Forshaw, Plätzer – arXiv:181y.xxxxx
Forshaw, Holguin, Plätzer – arXiv:181y.xxxxx

More on soft gluons beyond leading colour

Simon Plätzer

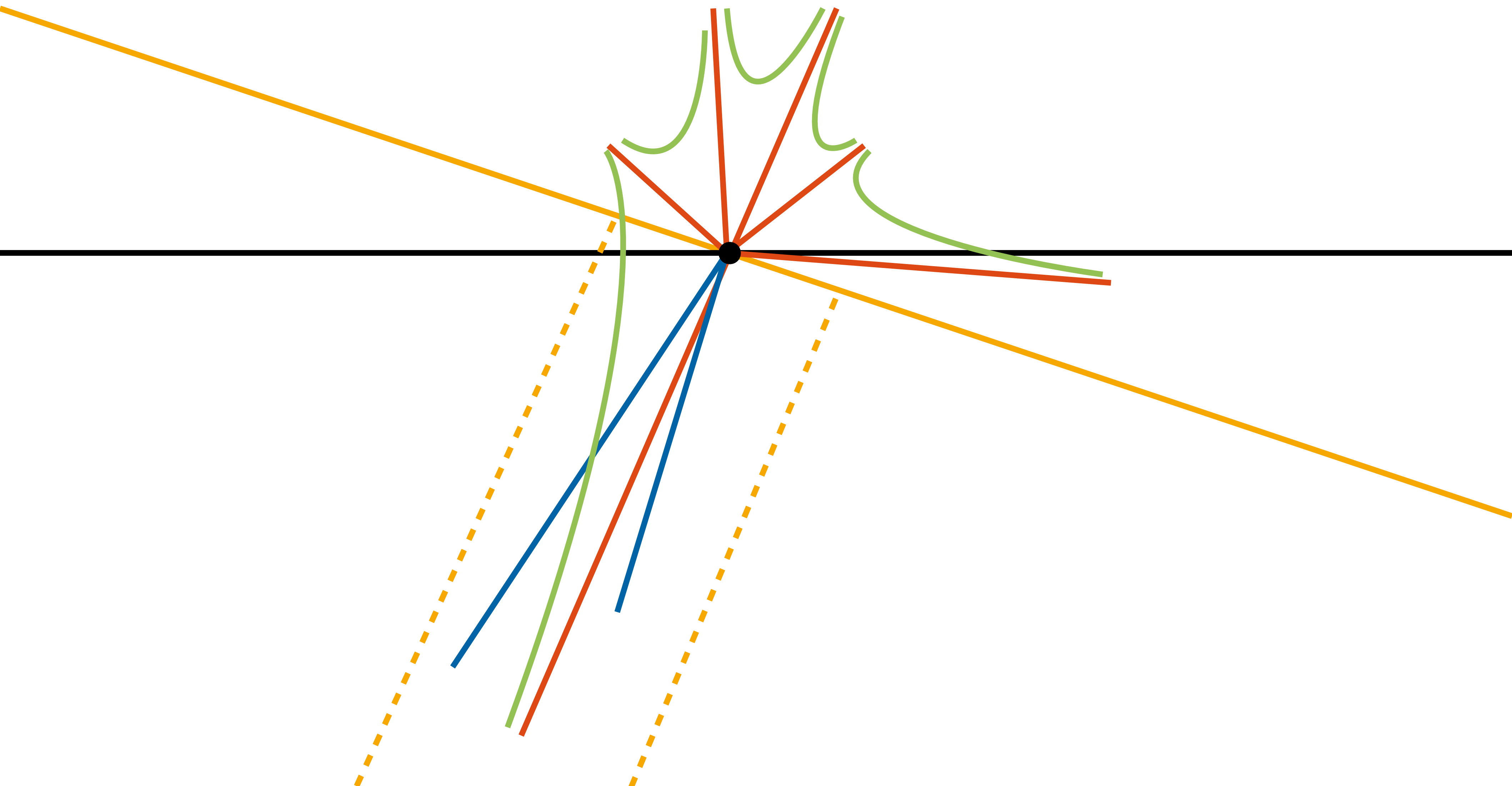
Particle Physics, University of Vienna

at the
HARPS Meeting
Genova | 13 September 2018

State of the art

Resummation of non-global observables is with dipole cascades in the large-N limit.

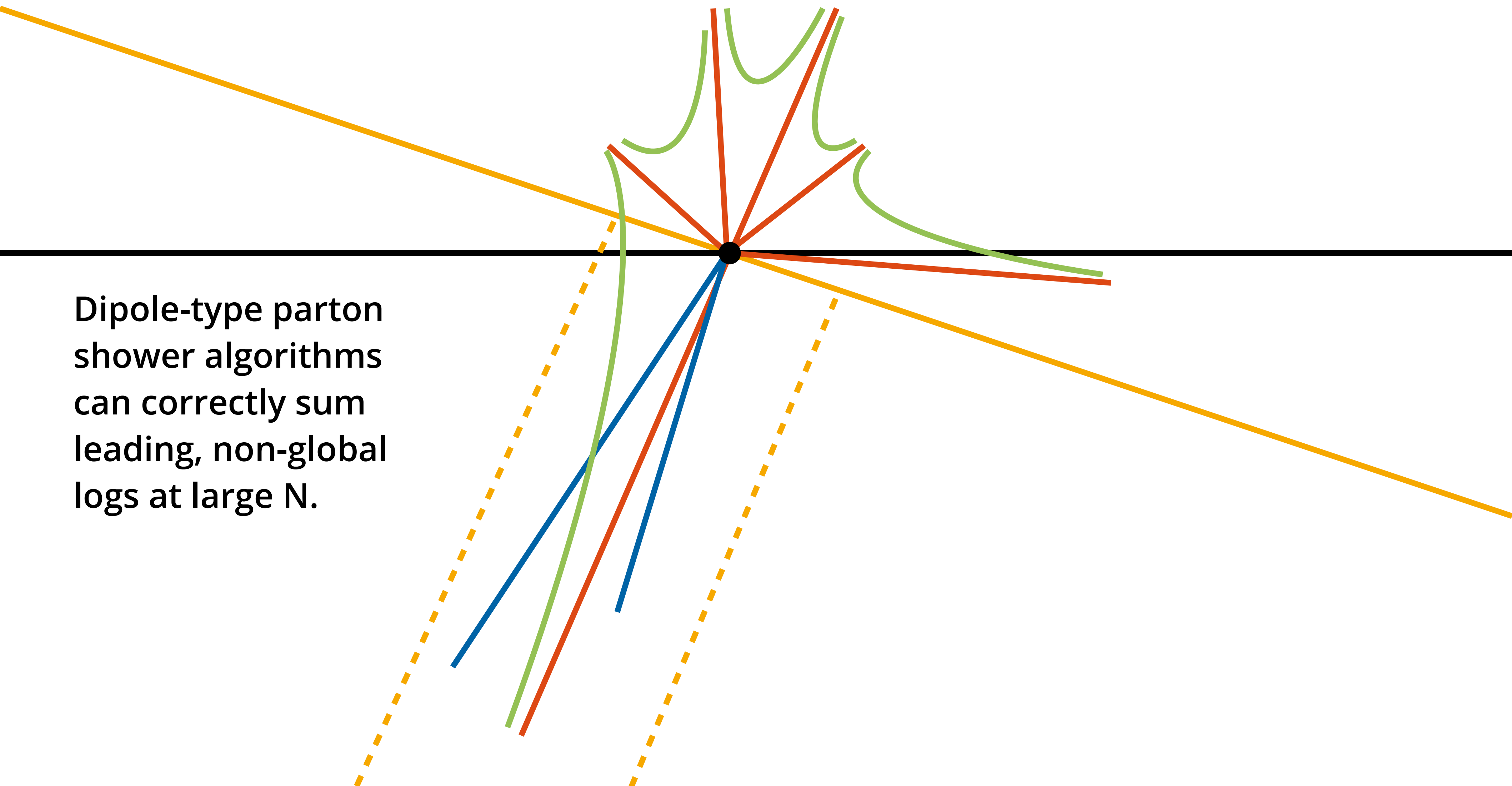
[Dasgupta, Salam – Phys.Lett. B512 (2001) 323]
[Balsinger, Becher, Shao – arXiv:1803.07045]



State of the art

Resummation of non-global observables is with dipole cascades in the large-N limit.

[Dasgupta, Salam – Phys.Lett. B512 (2001) 323]
[Balsinger, Becher, Shao – arXiv:1803.07045]

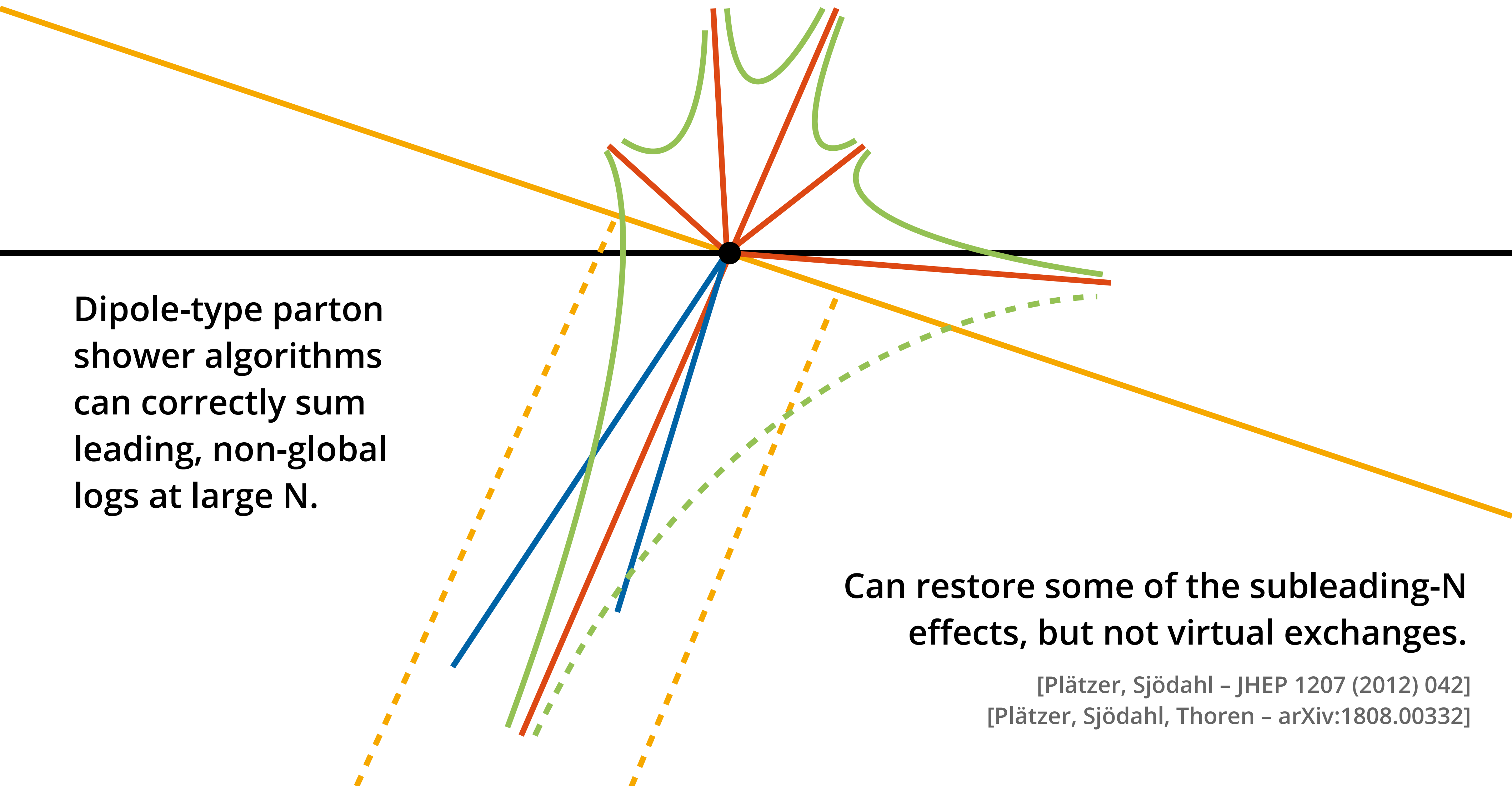


Dipole-type parton shower algorithms can correctly sum leading, non-global logs at large N.

State of the art

Resummation of non-global observables is with dipole cascades in the large-N limit.

[Dasgupta, Salam – Phys.Lett. B512 (2001) 323]
[Balsinger, Becher, Shao – arXiv:1803.07045]



Dipole-type parton shower algorithms can correctly sum leading, non-global logs at large N.

Can restore some of the subleading-N effects, but not virtual exchanges.

[Plätzer, Sjödahl – JHEP 1207 (2012) 042]
[Plätzer, Sjödahl, Thoren – arXiv:1808.00332]

Strategy and Goals

Seek a framework to systematically address and improve **a new kind of parton shower algorithm**, not relying on ad-hoc constructions, treating colour exactly as far as possible.

[also see Nagy, Soper]

Non-global observables are a unique playground: At large-N they provide a clean way of deriving a dipole-type parton shower, but the origin of the method used is much more general.

$$\sigma = \sum_n \int \mathrm{Tr}\left[\mathbf{A}_n(\mu)\right] u(p_1, ..., p_n)\ \mathrm{d}\phi_n$$

$$\mathbf{A}_n(\mu) = |\mathcal{M}_n(\mu)\rangle\langle\mathcal{M}_n(\mu)|$$

Evolved `density operator`

Observable

Phase space

A General Algorithm

universität wien

[Angeles, De Angelis, Forshaw, Plätzer, Seymour – JHEP 05 (2018) 044]

Successive virtual evolution/emission combinations down to an infrared cutoff, which will need to be removed at the end. Observable value itself can act as a cutoff, if fully inclusive for gluon energies below this scale.

$$\mathbf{A}_n(E) = \mathbf{V}(E, E_n)\mathbf{D}_n\mathbf{A}_{n-1}(E_n)\mathbf{D}_n^\dagger\mathbf{V}^\dagger(E, E_n)\theta(E - E_n)$$

$$\mathbf{V}_n(E, Q) = \mathrm{P}\exp\left(-\int_E^Q \frac{\mathrm{d}q}{q}\mathbf{\Gamma}_n(q)\right) \qquad \mathbf{D}_n = \sum_{i=1}^{n-1}\frac{p_i \cdot \epsilon^*(p_n)}{p_i \cdot p_n}\mathbf{T}_i$$

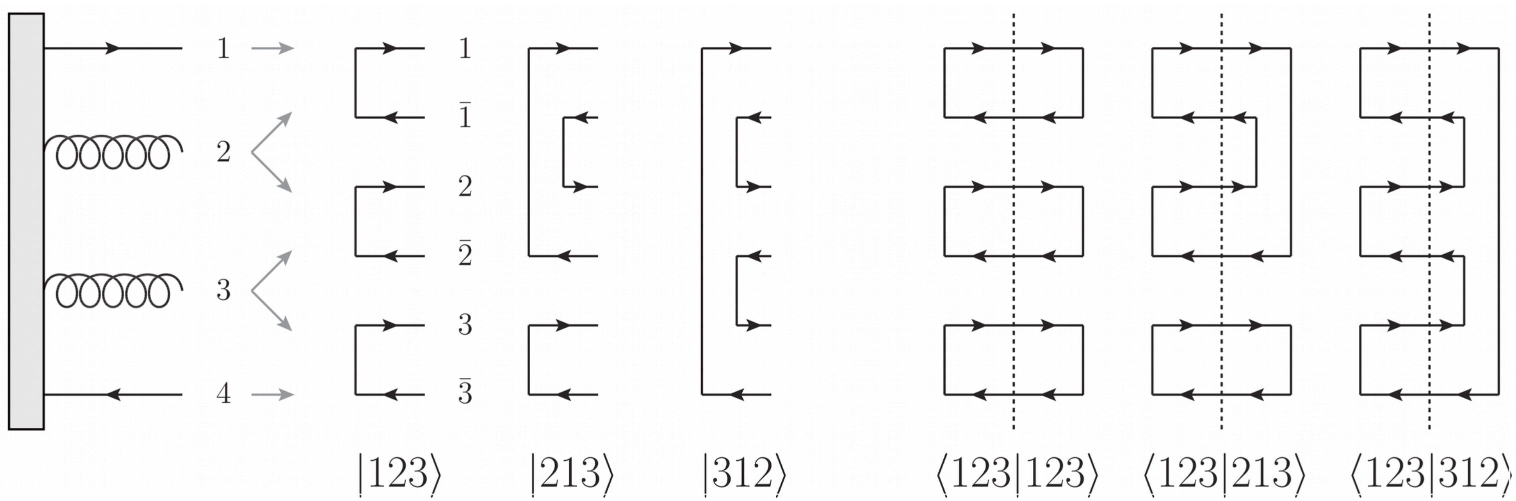
Non-probabilistic evolution at the amplitude level, keeping full colour structure, virtual corrections encoded in anomalous dimension

$$\mathbf{\Gamma}_n = \frac{\alpha_s}{\pi}\sum_{i<j}\int \mathrm{d}\Omega \frac{n_i \cdot n_j}{n_i \cdot n \; n \cdot n_j}(-\mathbf{T}_i \cdot \mathbf{T}_j)$$

Colour Flows

Express amplitudes in combinations of fundamental/anti-fundamental indices:

$$|\mathcal{M}\rangle = \sum_\sigma \mathcal{M}_\sigma |\sigma\rangle \qquad |\sigma\rangle = \left| \begin{matrix} 1 & \cdots & n \\ \sigma(1) & \cdots & \sigma(n) \end{matrix} \right\rangle = \delta^{\alpha_1}_{\bar{\alpha}_{\sigma(1)}} \cdots \delta^{\alpha_n}_{\bar{\alpha}_{\sigma(n)}}$$



Non-orthogonal basis:

$$1 = \sum_\sigma |\sigma\rangle[\sigma| \qquad [\sigma|\tau\rangle = \langle\sigma|\tau] = \delta_{\tau\sigma} \qquad \mathrm{Tr}[\mathbf{A}] = \sum_{\tau,\sigma} [\tau|\mathbf{A}|\sigma]\langle\sigma|\tau\rangle$$

Also overcomplete … but computationally very handy: It's all about permutations.

Resumming in Colour Space

universität wien

Evolution operator in colour flow basis:

$$[\tau|e^{\mathbf{\Gamma}}|\sigma\rangle = \sum_{k=0}^{\infty}\frac{(-1)^l}{N^l}\sum_{k=0}^{l}\frac{(-\rho)^k}{k!}\sum_{\sigma_0,\ldots,\sigma_{l-k}}\delta_{\tau\sigma_0}\delta_{\sigma_{l-k}\sigma}\prod_{\alpha=0}^{l-k-1}\Sigma_{\sigma_\alpha\sigma_{\alpha+1}}R(\{\sigma_0,\ldots,\sigma_{l-k}\})$$

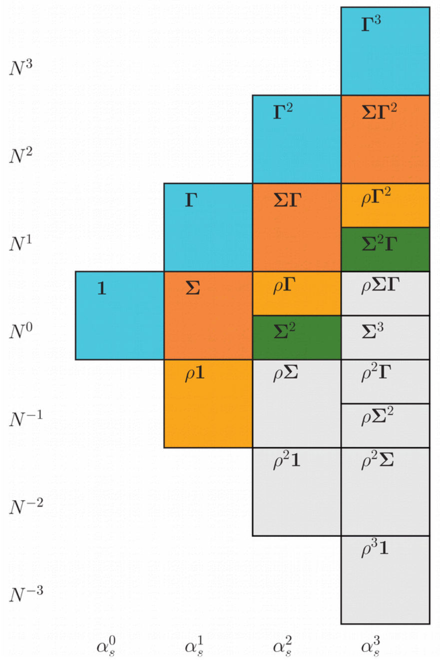
$$= \delta_{\tau\sigma}\left(e^{-N\Gamma_\sigma} + e^{-N\Gamma_\sigma}\frac{\rho}{N}\right) - \frac{1}{N}\frac{e^{-N\Gamma_\tau} - e^{-N\Gamma_\sigma}}{\Gamma_\tau - \Gamma_\sigma}\Sigma_{\tau\sigma} + \text{NNLC}$$

[Plätzer – EPJ C 74 (2014) 2907]

Sum terms enhanced by $\alpha_s N$ to all orders, insert perturbations in 1/N.

Take into account real emission contributions and the final suppression by the scalar product matrix element.

$$\mathrm{Tr}\,[\mathbf{A}] = \sum_{\tau\sigma}[\tau|\mathbf{A}|\sigma]\langle\sigma|\tau\rangle \qquad \langle\sigma|\tau\rangle = N^{n-\#(\tau,\sigma)}$$



virtuals	reals
$(0\text{ flips}) \times 1 \times (\alpha_s N)^n$	$(\mathbf{t}[\ldots]\mathbf{t}\|_{0\text{ flips}})^{r-1}\ \mathbf{t}[\ldots]\mathbf{t}\|_{2\text{ flips}} \times 1$ $(\mathbf{t}[\ldots]\mathbf{t}\|_{0\text{ flips}})^{r-1}\ \mathbf{t}[\ldots]\mathbf{s}\|_{1\text{ flip}} \times N^{-1}$ $(\mathbf{t}[\ldots]\mathbf{t}\|_{0\text{ flips}})^{r-1}\ \mathbf{s}[\ldots]\mathbf{s}\|_{0\text{ flips}} \times N^{-2}$
$(1\text{ flip}) \times \alpha_s \times (\alpha_s N)^n$	$(\mathbf{t}[\ldots]\mathbf{t}\|_{0\text{ flips}})^{r}$ $(\mathbf{t}[\ldots]\mathbf{t}\|_{0\text{ flips}})^{r-1}\ \mathbf{t}[\ldots]\mathbf{s}\|_{1\text{ flip}} \times N^{-1}$
$(0\text{ flips}) \times \alpha_s N^{-1} \times (\alpha_s N)^n$	$(\mathbf{t}[\ldots]\mathbf{t}\|_{0\text{ flips}})^{r}$
$(0\text{ flips}) \times \alpha_s^2 \times (\alpha_s N)^n$ $(2\text{ flips}) \times \alpha_s^2 \times (\alpha_s N)^n$	$(\mathbf{t}[\ldots]\mathbf{t}\|_{0\text{ flips}})^{r}$ $(\mathbf{t}[\ldots]\mathbf{t}\|_{0\text{ flips}})^{r-1}\ \mathbf{t}[\ldots]\mathbf{t}\|_{2\text{ flips}}$

Resumming in Colour Space

Evolution operator in colour flow basis:

$$[\tau|e^{\mathbf{\Gamma}}|\sigma\rangle = \sum_{k=0}^{\infty}\frac{(-1)^l}{N^l}\sum_{k=0}^{l}\frac{(-\rho)^k}{k!}\sum_{\sigma_0,\dots,\sigma_{l-k}}\delta_{\tau\sigma_0}\delta_{\sigma_{l-k}\sigma}\prod_{\alpha=0}^{l-k-1}\Sigma_{\sigma_\alpha\sigma_{\alpha+1}}R(\{\sigma_0,\dots,\sigma_{l-k}\})$$

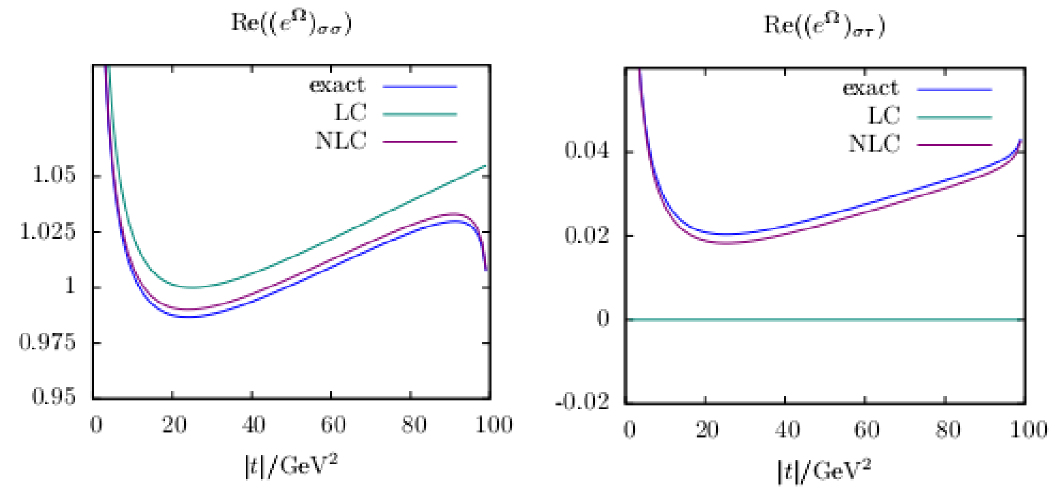
$$= \delta_{\tau\sigma}\left(e^{-N\Gamma_\sigma} + e^{-N\Gamma_\sigma}\frac{\rho}{N}\right) - \frac{1}{N}\frac{e^{-N\Gamma_\tau} - e^{-N\Gamma_\sigma}}{\Gamma_\tau - \Gamma_\sigma}\Sigma_{\tau\sigma} + \mathrm{NNLC}$$

[Plätzer – EPJ C 74 (2014) 2907]

Sum terms enhanced by $\alpha_s N$ to all orders, insert perturbations in 1/N.

Take into account real emission contributions and the final suppression by the scalar product matrix element.

$$\mathrm{Tr}\,[\mathbf{A}] = \sum_{\tau\sigma}[\tau|\mathbf{A}|\sigma]\langle\sigma|\tau\rangle \qquad \langle\sigma|\tau\rangle = N^{n-\#(\tau,\sigma)}$$



Basic algorithm

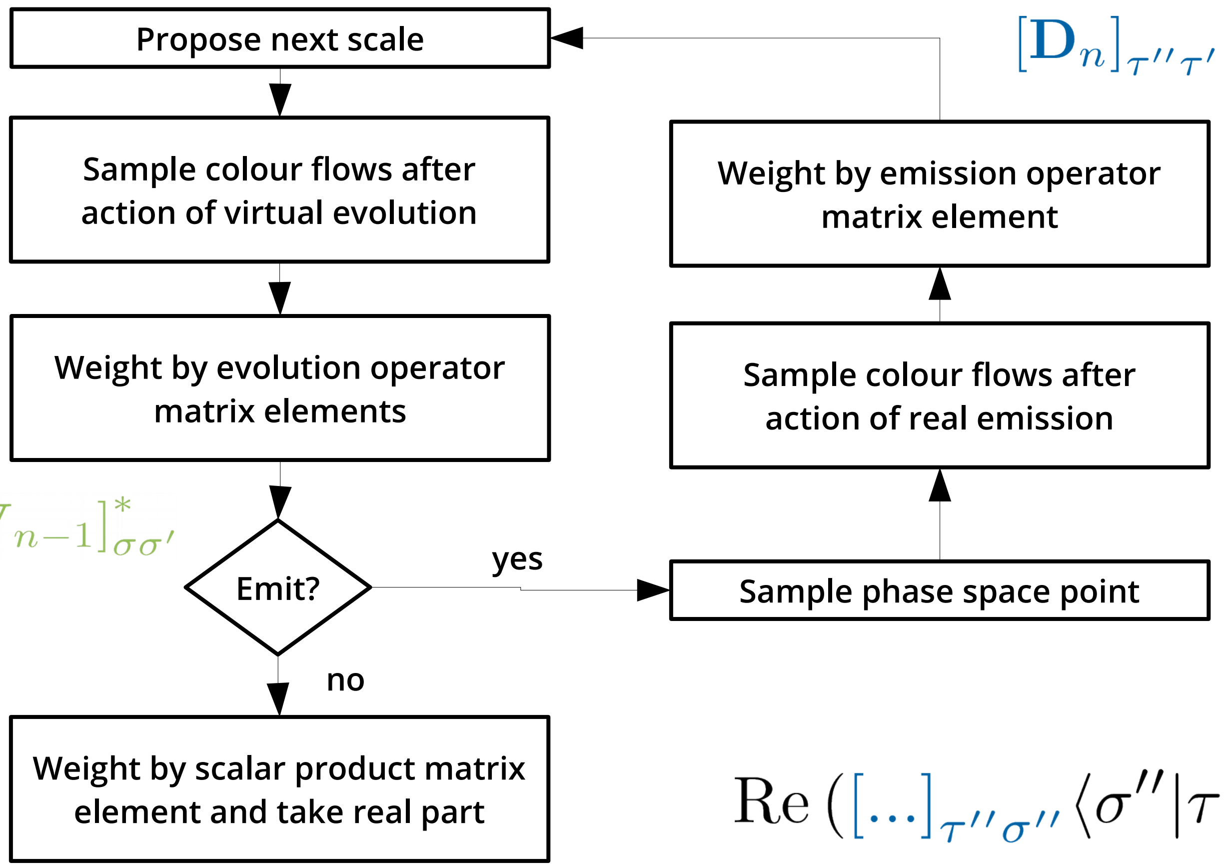
[De Angelis, Forshaw, Plätzer – arXiv:181y.xxxxx]

$$\mathbf{A}_n(E) = \mathbf{V}(E, E_n)\mathbf{D}_n\mathbf{A}_{n-1}(E_n)\mathbf{D}_n^\dagger\mathbf{V}^\dagger(E, E_n)\theta(E - E_n)$$

$$[\mathbf{M}_{n-1}]_{\tau\sigma}$$

$$\tau\sigma \to \tau'\sigma'$$

$$[\mathbf{V}_{n-1}]_{\tau'\tau}[\ldots]_{\tau\sigma}[\mathbf{V}_{n-1}]^*_{\sigma\sigma'}$$



$$[\mathbf{D}_n]_{\tau''\tau'}[\ldots]_{\tau'\sigma'}[\mathbf{D}_n]^*_{\sigma'\sigma''}$$

$$\sigma', \tau' \to \sigma'', \tau''$$

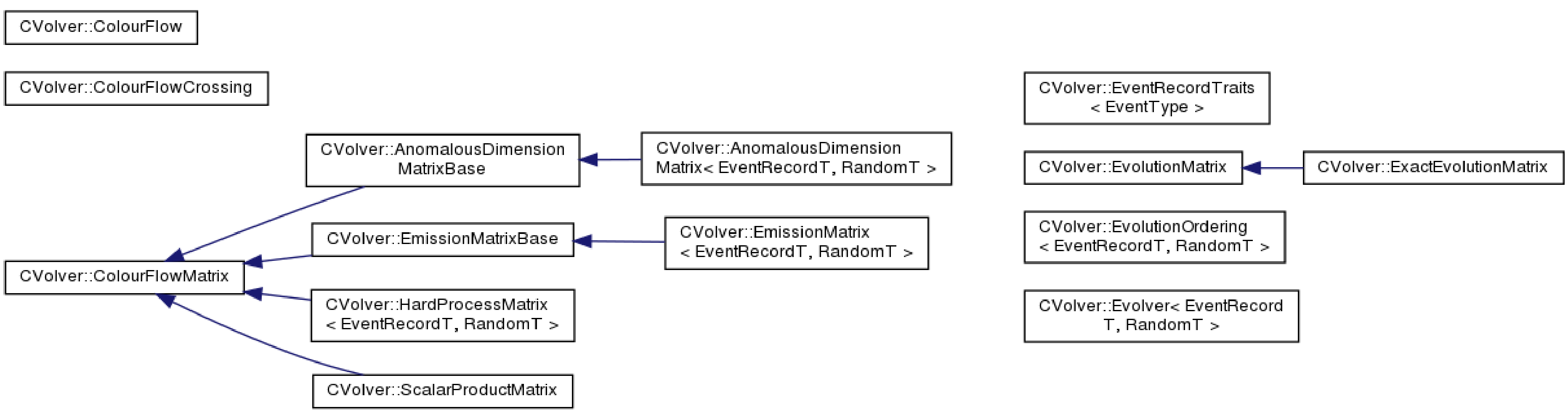
$$\mathrm{Re}\left([\ldots]_{\tau''\sigma''}\langle\sigma''|\tau''\rangle\right)$$

Exploring Colours with CVolver

[De Angelis, Forshaw, Plätzer – arXiv:181y.xxxxx]

A framework to solve multi-differential evolution equations in colour space.
Concise, simple, and light-weight code structure.

$$\mathbf{A}_n(E) = \mathbf{V}(E, E_n)\mathbf{D}_n\mathbf{A}_{n-1}(E_n)\mathbf{D}_n^\dagger\mathbf{V}^\dagger(E, E_n)\theta(E - E_n)$$



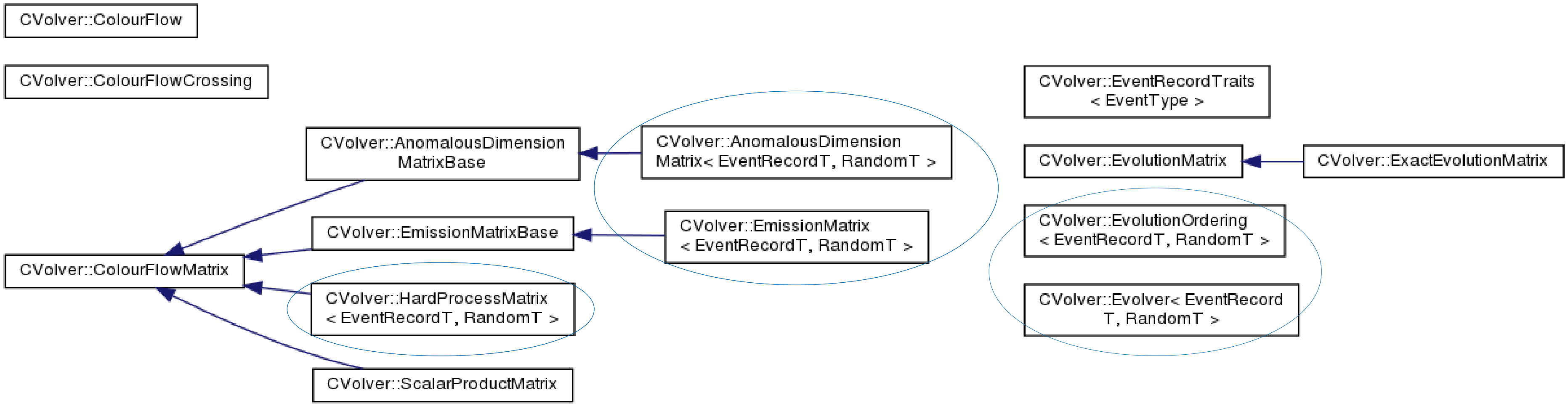
Dedicated Monte Carlo algorithms to sample colour structures.
Plugin approach can accommodate anything from (N)GLs to full parton showers.

Exploring Colours with CVolver

[De Angelis, Forshaw, Plätzer – arXiv:181y.xxxxx]

A framework to solve multi-differential evolution equations in colour space.
Concise, simple, and light-weight code structure.

$$\mathbf{A}_n(E) = \mathbf{V}(E, E_n)\mathbf{D}_n\mathbf{A}_{n-1}(E_n)\mathbf{D}_n^\dagger\mathbf{V}^\dagger(E, E_n)\theta(E - E_n)$$

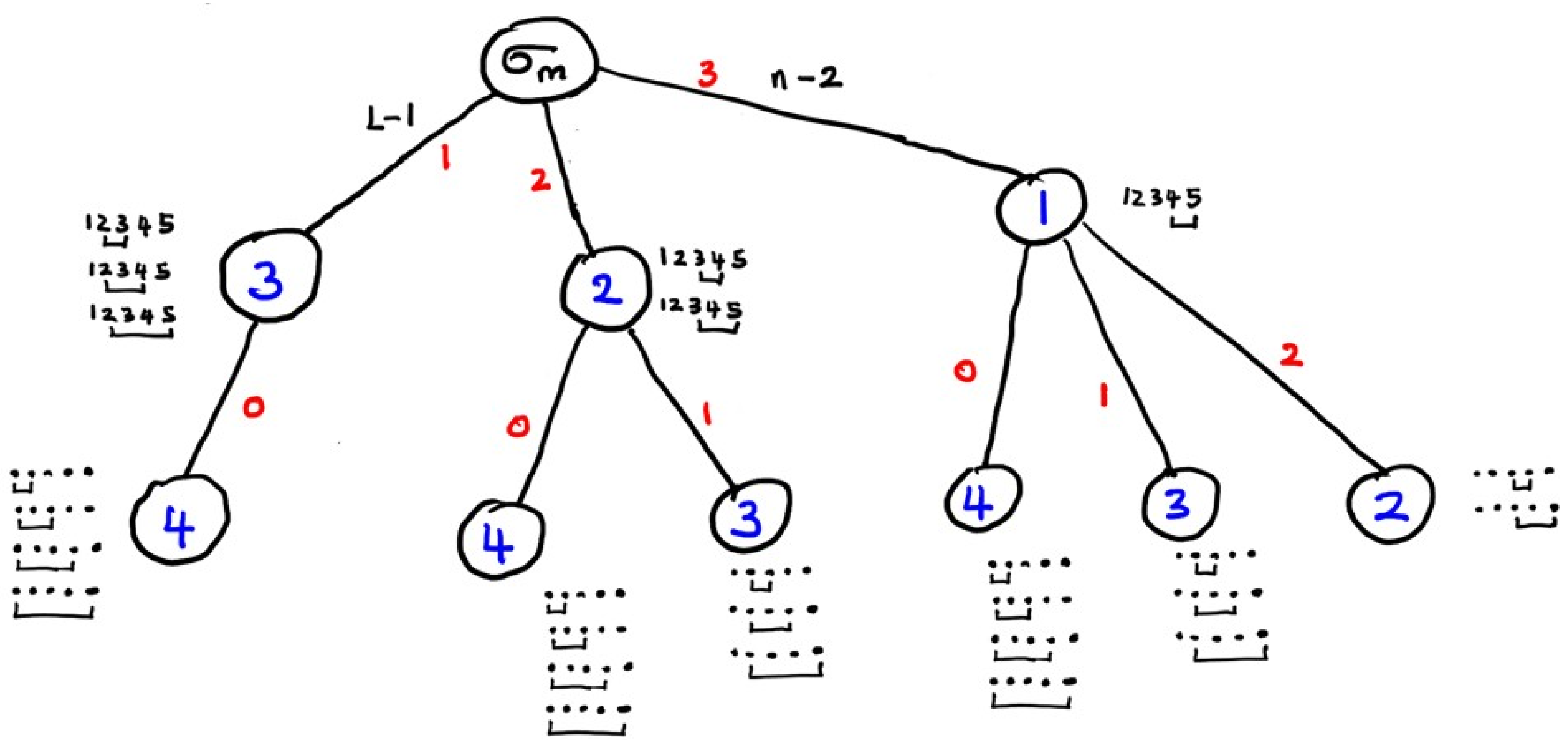


Dedicated Monte Carlo algorithms to sample colour structures.
Plugin approach can accommodate anything from (N)GLs to full parton showers.

Importance Sampling in Colour Space

Importance sampling in colour space rules: $\#(\tau,\tau') \sim 1/N^{\#(\tau,\tau')}$

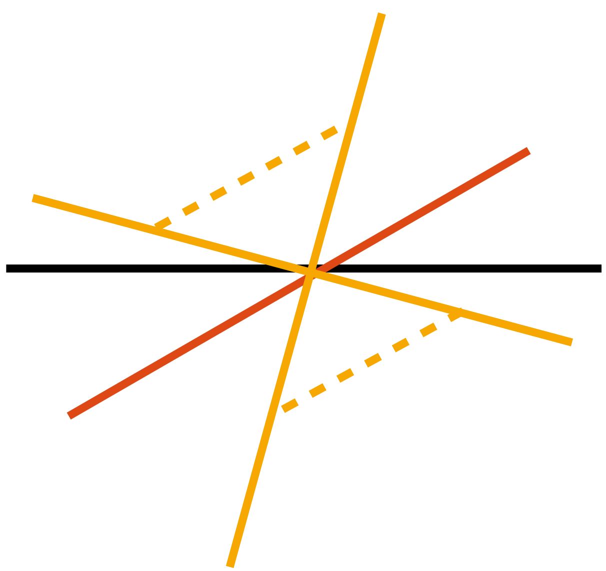
Enumerate and address permutations with fixed cycle length:

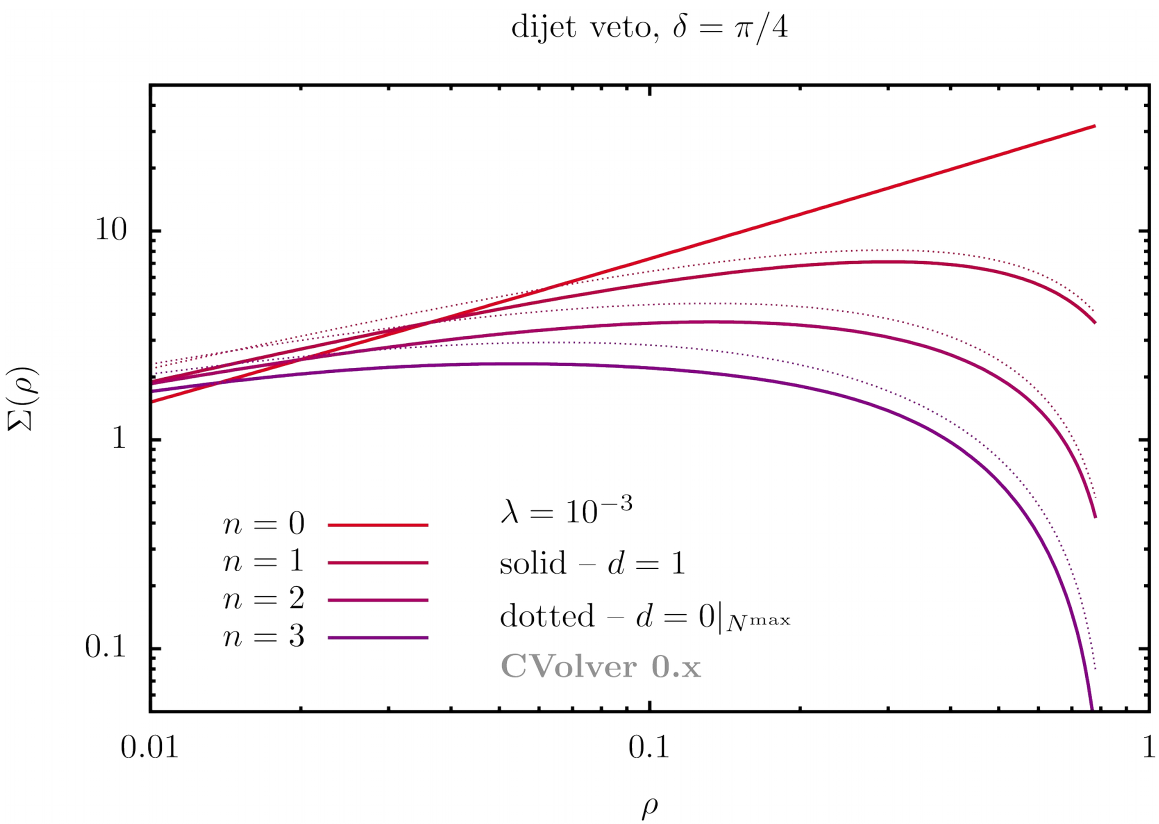


Numerical Results from CVolver

[De Angelis, Forshaw, Plätzer – arXiv:181y.xxxxx]

Code is differential for a large class of (non-global) observables.
Example: Cone-dijet veto cross section.





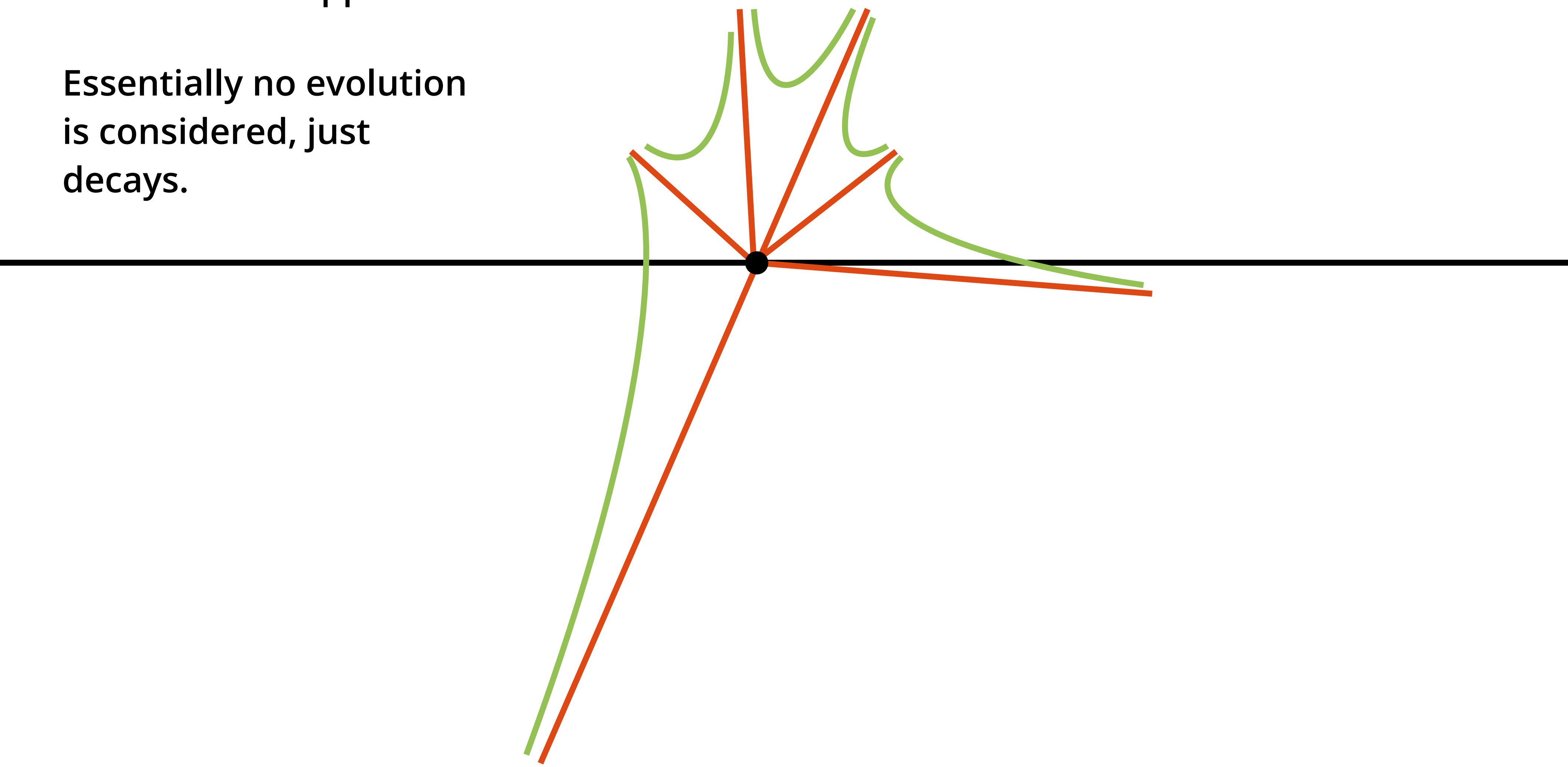
1/N breakdowns possible, scales up to several 10s of emissions for d=2.

A Fresh Look at Colour Reconnection Models

[Gieseke, Kirchgaesser, Plätzer, Siodmok – arXiv:1808.06770]

The cluster model is based on a single colour flow after the shower has stopped.

Essentially no evolution is considered, just decays.



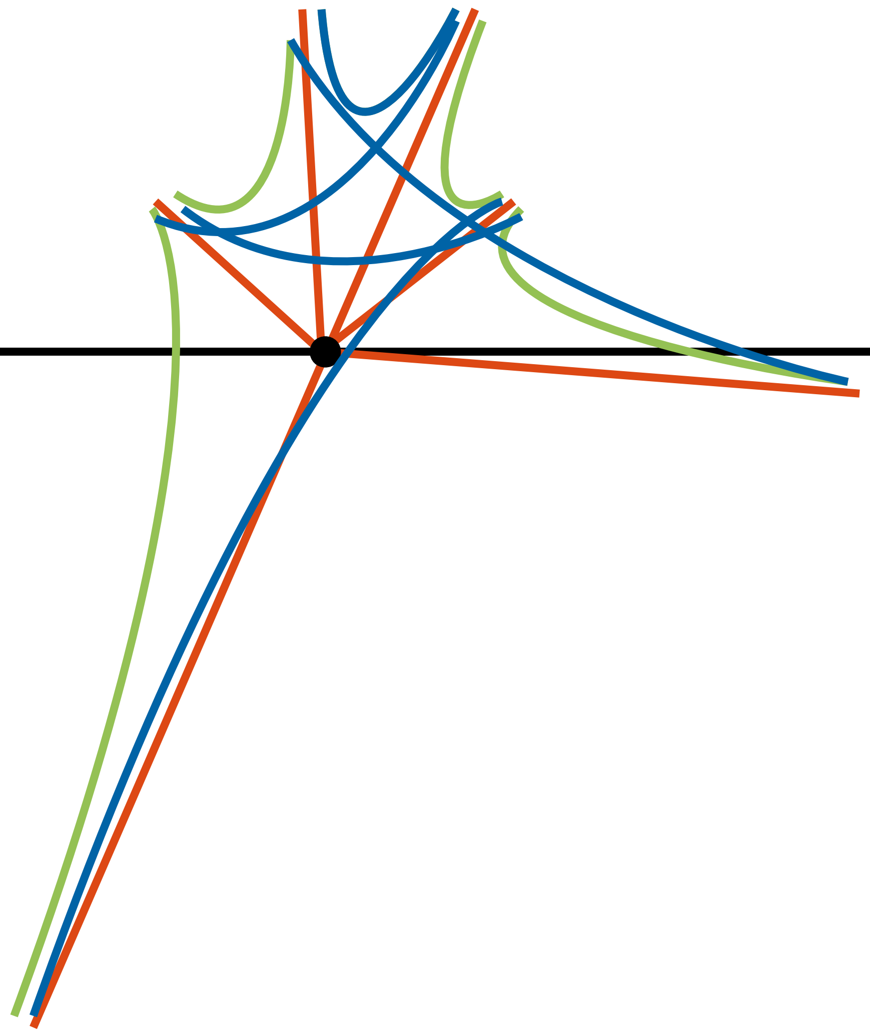
A Fresh Look at Colour Reconnection Models

universität wien

[Gieseke, Kirchgaesser, Plätzer, Siodmok – arXiv:1808.06770]

The cluster model is based on a single colour flow after the shower has stopped.

Essentially no evolution is considered, just decays.

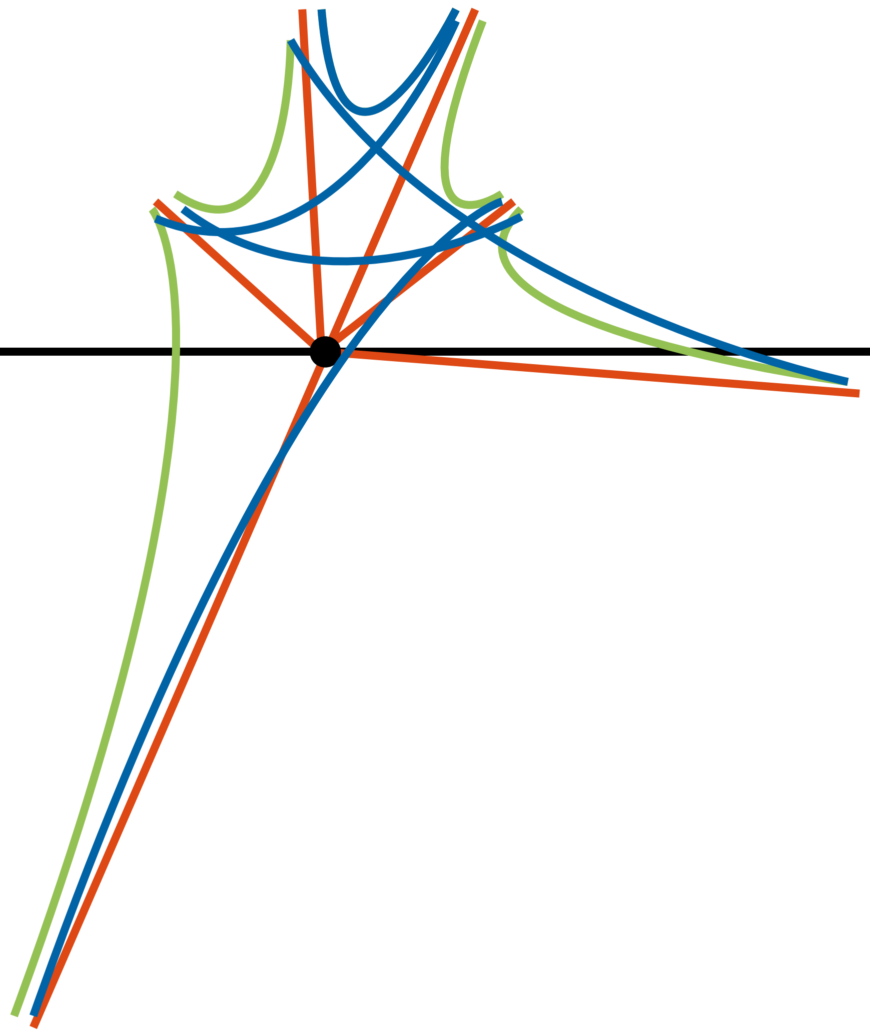


A Fresh Look at Colour Reconnection Models

[Gieseke, Kirchgaesser, Plätzer, Siodmok – arXiv:1808.06770]

The cluster model is based on a single colour flow after the shower has stopped.

Essentially no evolution is considered, just decays.



View as an evolving amplitude, driven by a single initial colour flow:

$$|\mathcal{M}\rangle = e^{\mathbf{\Gamma}}|\text{clusters}\rangle$$

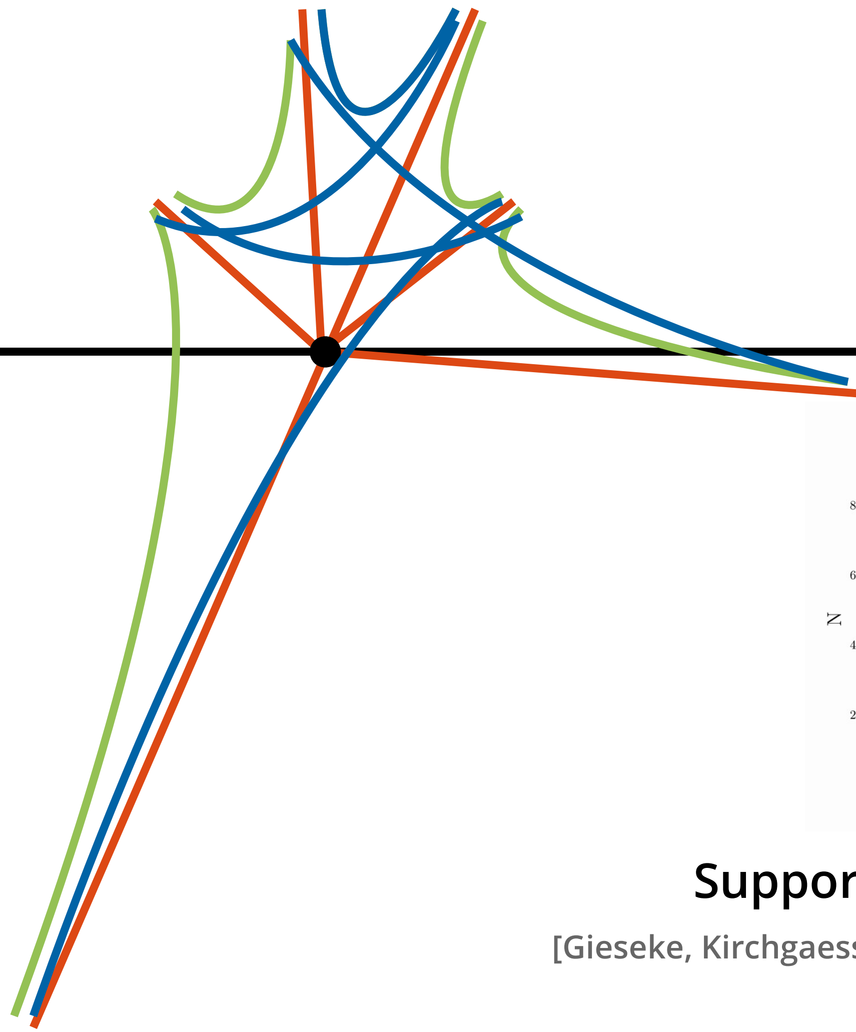
$$P_{\text{reco}} \sim |\langle\text{clusters'}|\mathcal{M}\rangle|^2$$

A Fresh Look at Colour Reconnection Models

[Gieseke, Kirchgaesser, Plätzer, Siodmok – arXiv:1808.06770]

The cluster model is based on a single colour flow after the shower has stopped.

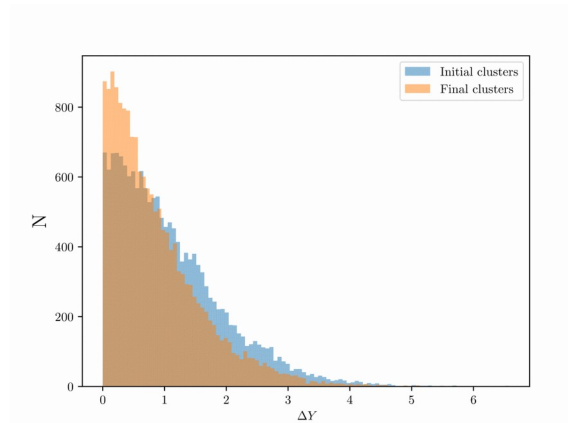
Essentially no evolution is considered, just decays.



View as an evolving amplitude, driven by a single initial colour flow:

$$|\mathcal{M}\rangle = e^{\mathbf{\Gamma}}|\text{clusters}\rangle$$

$$P_{\text{reco}} \sim |\langle\text{clusters'}|\mathcal{M}\rangle|^2$$



Supports geometric models

[Gieseke, Kirchgaesser, Plätzer – EPJ C 78 (2018) 99]

Summary & Outlook

A framework for amplitude-level evolution at full colour, including a Monte Carlo method to produce actual `events'.

Serves to host a new approach to parton shower algorithms, which are systematically improvable, and first steps in that direction are underway.

Resummation of non-global observables requires the very same methods, and so provide an ideal playground to quantify these effects in a controlled way.

Details of colour expansion under study.

Beyond the perturbative evolution this provides us with unique insight into colour reconnection models.