Parton shower: Overview

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Disclaimer

This talk aims at highlighting current developments in parton showers and the driving forces behind them. It can neither be a complete account of all current research topics nor can it go into any detail. I simply hope it will be a starting point for discussion.

The selection is surely biased, and I apologise for leaving some important ones out.

Outline

General considerations

General form

$$\mathrm{PS}_n(t_c, t_{\max}) = \Delta_n(t_c, t_{\max}) + \int_{t_c}^{t_{\max}} \mathrm{d}t' \, \mathcal{K}_n(t') \, \Delta_n(t', t_{\max})$$

- splitting kernel $\mathcal{K}_n = \sum_{i=1}^{n} \mathcal{K}_i$, with collinear limit $\mathcal{K}_i \to \frac{\alpha_s}{2\pi t} P(z)$
  n number of emitter (partons, dipoles, etc.)
- evolution variable t, splitting variable z
- usually independent of azimuthal angle ϕ
  $\to$ spin-avaraged
- choose $\alpha_s = \alpha_s(k_\perp^2)$ to resum certain class of higher logs from 1-loop running
- recoil scheme only needs to be infrared safe
  $\to$ implements momentum conservation

General considerations

PS	Splitting function	Recoil scheme	Construction
PYTHIA8	$1 \to 2$	Local	DGLAP
HERWIG++ (angular)	$1 \to 2$	Global	DGLAP
HERWIG++ (dipole)	$1 \to 2$	Local	CS Dipoles
SHERPA/CSSHOWER++	$1 \to 2$	Local	CS Dipoles
ARIADNE	$2 \to 3$	Local	Antenna
VINCIA	$2 \to 3$	Local	Antenna
SHERPA/ANTS	$2 \to 3$	Local	Antenna
KRKMC	$1 \to 2$	Global	DGLAP
DEDUCTOR	$n \to n+1$	Local	NS subtraction
⋮			

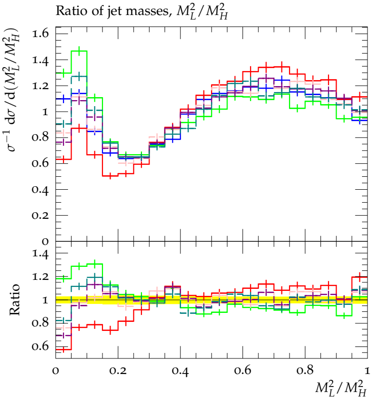
Impact of choices

Choices:

- precise definition of evolution variable,
  only needs to behave as $\frac{\mathrm{d}t}{t} = \frac{\mathrm{d}p_\perp^2}{p_\perp^2}$ in the collinear limit
  $\rightarrow p_\perp^2$, θ, $\tilde{p}_\perp^2$, ...
- recoil scheme, only needs to be IR-safe
  $\rightarrow$ at most power corrections, but can be numerically sizeable
- power corrections and finite terms in splitting functions
  $\rightarrow$ (generalised) matrix element corrections
- α_s-running beyond 1-loop
  $\rightarrow$ fix 1-loop running to $\alpha_s(k_\perp)$ by counterterm
- $g \rightarrow q\bar{q}$ splittings have no LL, free to choose α_s-scale

Choice of ordering variable and recoil scheme

Fischer, Gieseke, Plätzer, Skands EPJC74(2014)2831



Generator	Recoil	Evolution
HERWIG++	Global	$\tilde{q}^2$
HERWIG++	Dipole	$p_{\perp\text{dip}}^2$
HERWIG++	Dipole	q_{dip}^2
PYTHIA8	Dipole	$p_\perp^2$
VINCIA	Antenna	$p_{\perp\text{ant}}^2$
VINCIA	Antenna	m_{ant}^2

investigate 4-jet observables sensitive to subleading structure of PS

- ratio of hemisphere masses in events with compressed scale hierachy

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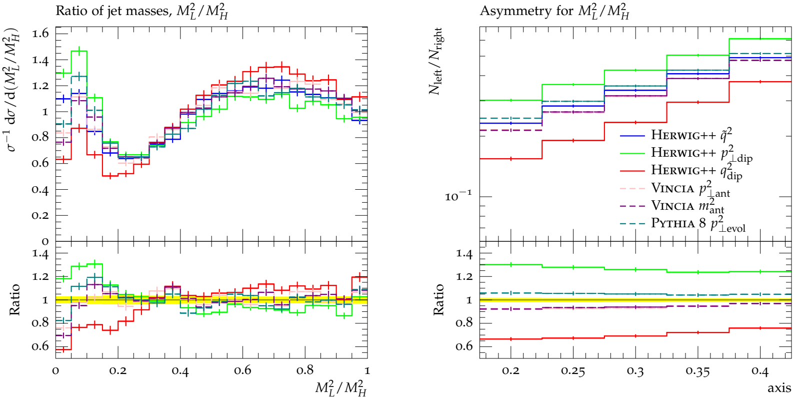

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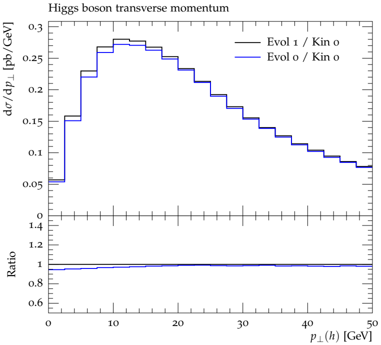
Höche, Krauss, MS arXiv:1401.7971



two evolution variables

	Final State
0	$2\,p_i p_j\,\tilde{z}_{i,jk}(1-\tilde{z}_{i,jk})$
1	$2\,p_i p_j \begin{cases} \tilde{z}_{i,jk}(1-\tilde{z}_{i,jk}) & \text{if } i,j=g \\ 1-\tilde{z}_{i,jk} & \text{if } j=g \\ \tilde{z}_{i,jk} & \text{if } i=g \\ 1 & \text{else} \end{cases}$
	Initial State
0	$2\,p_a p_j\,(1-x_{aj,k})$
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two recoil schemes

0	initial state as if final state + $\perp$-boost Höche, Schumann, Siegert Phys.Rev.D81(2010)034026
1	original CS Catani, Seymour Nucl.Phys.B485(1997)291-419 Schumann, Krauss JHEP03(2008)038

$\rightarrow$ similar ideas in Gieseke, Plätzer JHEP01(2011)024

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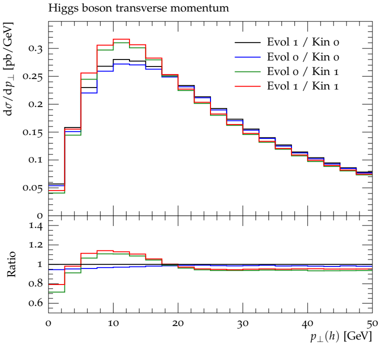

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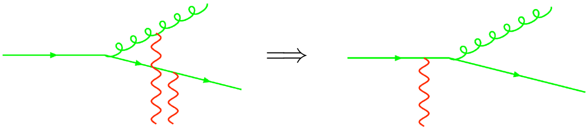
Colour coherence

Correlation of 2nd & 3rd jet, e.g.

$$\tan\beta = \frac{|\Delta\phi_{23}|}{\Delta\eta_{23}}$$

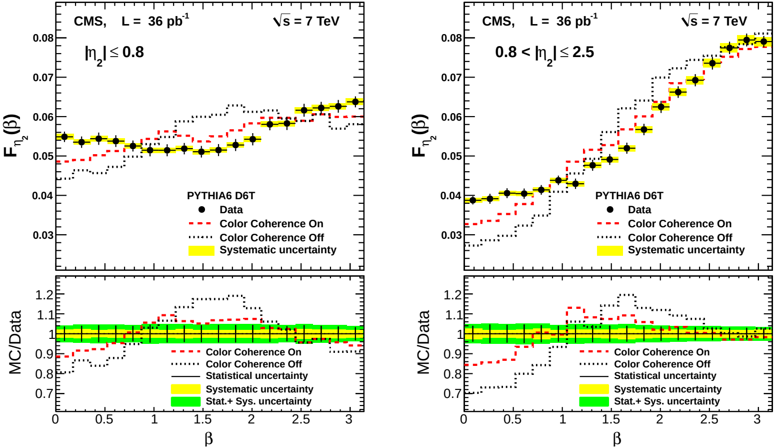
- probes description of soft emissions
- traditionally desribed through angular ordering or angular veto



- can also be described by explicit inclusion of soft limit in splitting function

Colour coherence

CMS arXiv:1311.5815



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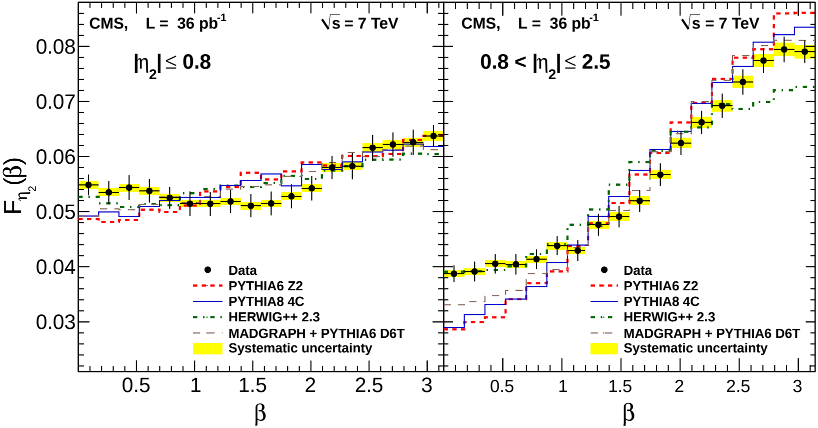

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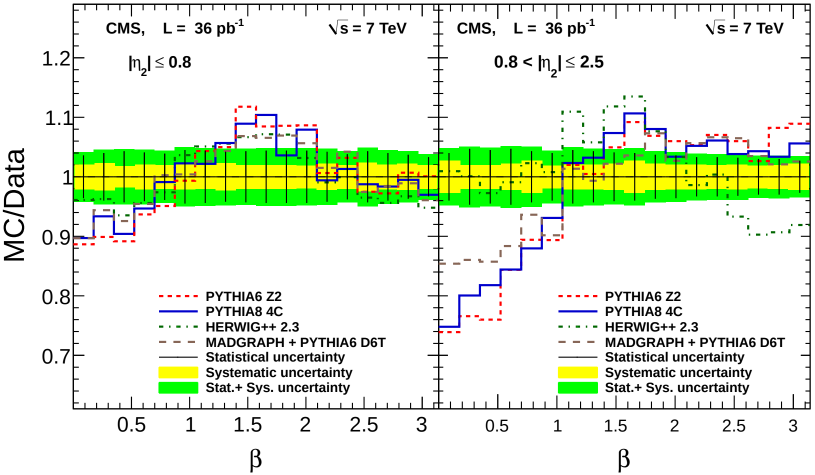

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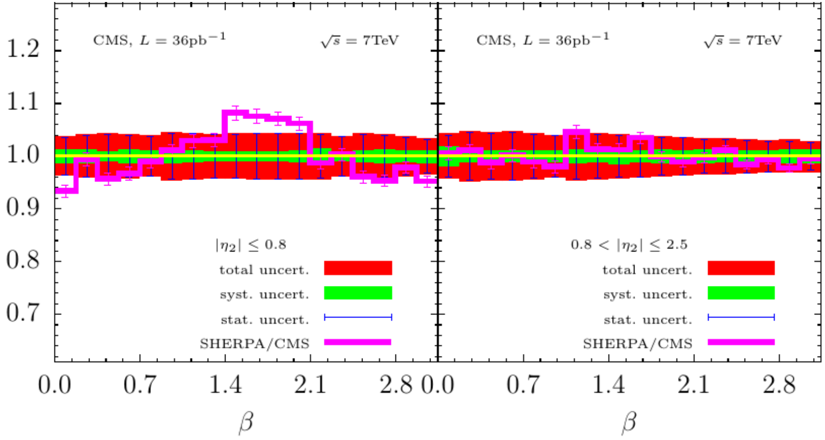


General considerations

- parton showers are well controlled fully differential resummation tools
- approximations made are solely related to the quality of the description of the soft-collinear limit
  (leading colour, spin-avaraging, perturbative order of splitting functions)

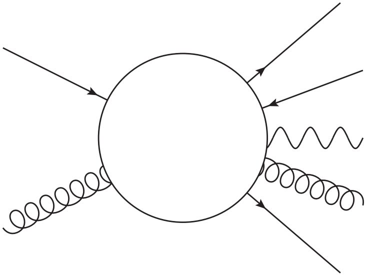
$\Rightarrow$ can be systematically improved

- no approximations in momentum conservation
- no additional restrictions on secondary radiation entering observable

$\Rightarrow$ formulation independent of observable definition

Radiation off multileg matrix elements

Consider showering a multileg matrix element, say $pp \to V + 4$ jets with all $Q_i > Q_{\text{min}}$ (Q some particle distance measure, e.g. jet algorithm)



- start showering from smallest Q_i, or
- reconstruct smallest $t = t_l$ and start showering from t_l
- no resummation for $t > t_l$

$\Rightarrow$ if $Q = t$ resummation active only for intrajet evolution below t_{min}

$\Rightarrow$ continous resummation only for $t < Q_{\text{min}}$

$\Rightarrow$ for $Q \neq t$ no well-defined structure of resummation as Q_{min} does not translate into a t_{min}

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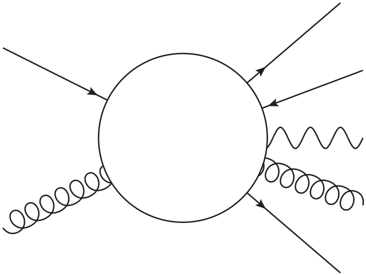

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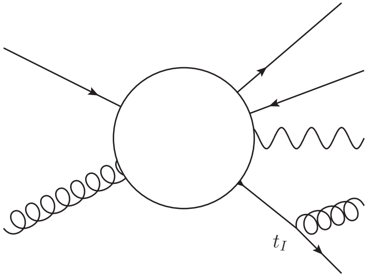

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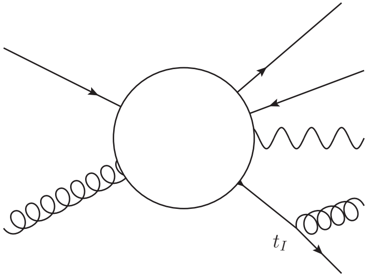

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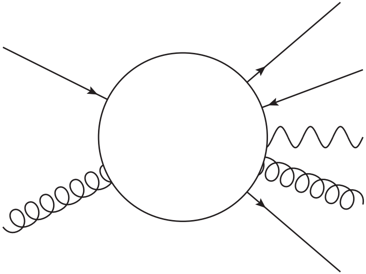

- reconstruct all emission scales t_i
- set starting scale t_I and start showering from there

$\Rightarrow$ embed existing emissions into evolution, veto any emission harder than existing Q_i

$\Rightarrow$ $pp \to V + 4$ jets configuration with consistent resummation of emission scale hierarchies, including the 4 existing ones

$\Rightarrow$ truncated (vetoed) showers

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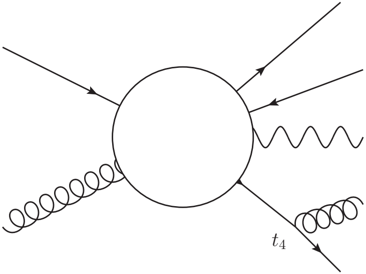

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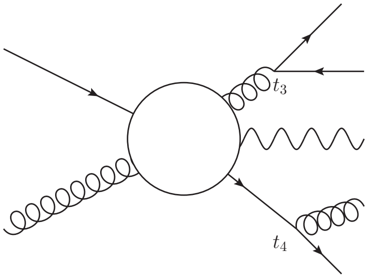

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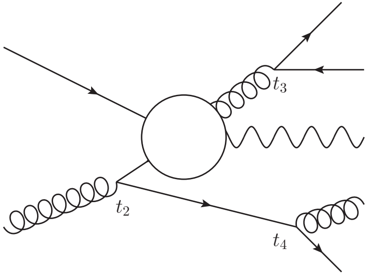

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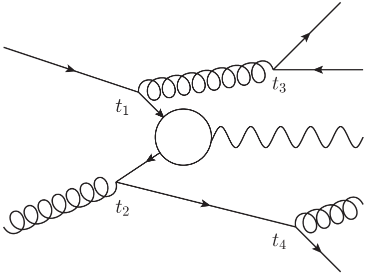

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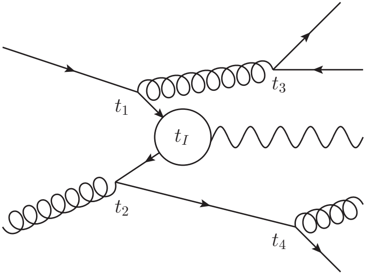

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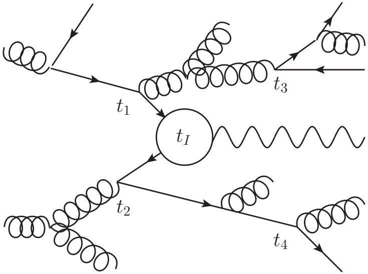

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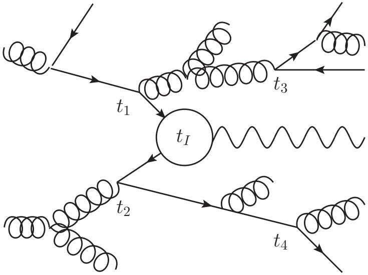

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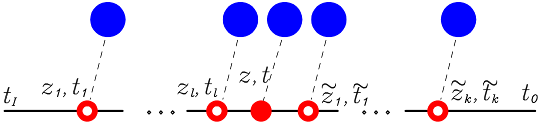
Truncated showering

Nason JHEP11(2004)040

Truncated showering is always needed when the hardness measure Q, defining which emissions are to be described by LO/NLO matrix elements, and the parton shower evolution variable t do not coincide.

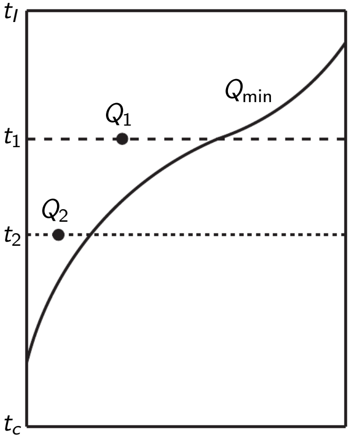


$$t_I > t_1 > \ldots > t_{i-1} > \mathbf{t}_i > t_{i+1} > \ldots > t_c \quad \text{but} \quad Q_i > Q_j \;\; \forall\, j \neq i$$

⇒ otherwise the resummation of the parton shower will be incomplete

⇒ in principle can change shower scheme after every emission if truncated shower fills in the gaps

Truncated showering



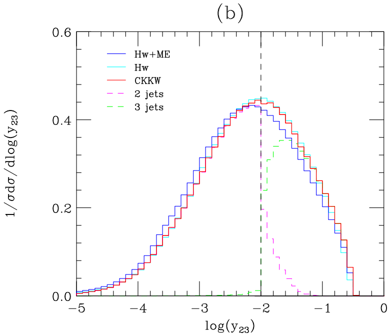
- starting shower at Q_{min} not well defined, as translation $Q \to t$ phase space dependent
- starting shower at reconstructed $t_2 = t(Q_2)$ leaves large parts of phase space empty and double counts region with $t < t_2$ and $Q > Q_{\mathrm{min}}$

$\Rightarrow$ shower need to start from t_I, veto emissions with $Q > Q_{\mathrm{min}}$, emissions at (t_1, z_1) and (t_2, z_2) must be preserved

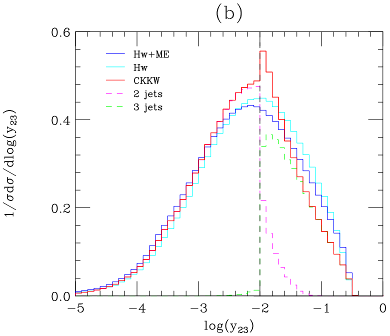
$\Rightarrow$ Multileg matrix elements necessitate truncated (vetoed) showering if $t \neq Q$

Importance of truncated showering

Hamilton, Richardson, Tully JHEP11(2009)038



w/ truncated PS



w/o truncated PS

- if Q and t differ then Sudakovs factors/emission probability underestimated for $t > Q$

Parton showers and NLO matching

$$\mathrm{d}\sigma^{\text{NLOPS}} = \mathrm{d}\Phi_B \left[\mathrm{B} + \mathrm{V} + \sum_i \int \mathrm{d}\Phi_1^i \, \mathrm{D}_i \right] \otimes \widetilde{\mathrm{PS}}_{\mathrm{D}} + \mathrm{d}\Phi_R \left[\mathrm{R} - \sum_i \mathrm{D}_i \right]$$

- emission kernels D_i used for IR subtraction
- problem 1: standard parton shower kernels in $N_c \to \infty$ limit
  $\to$ missing $1/N_c$ contributions, spoil soft limit
- incorporate $N_c = 3$ in the emission kernel D_i
- problem 2: standard parton shower kernels are spin avaraged
  $\to$ spin dependence of collinear limit of gluon splittings spoiled
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$\Rightarrow$ solved in different ways in different schemes

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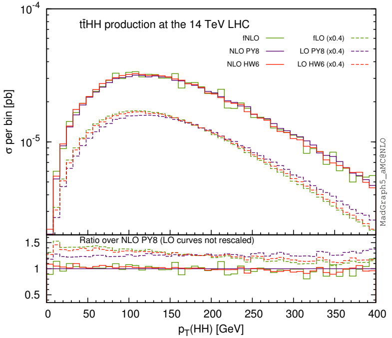
Subleading colours and spin correlations in trad. MC@NLO

Frixione, Webber JHEP06(2002)029; Frixione, Nason, Webber JHEP08(2003)007

- use $\mathrm{D}_i = f \cdot \mathcal{K}_i$
- use f to restore spin and colour correlations in standard shower
- for $f \equiv 1$ $(t > t_c)$ all resummation is embedded in standard shower

$\Rightarrow$ trivially consistent resummation



Alwall et.al. arXiv:1405.0301

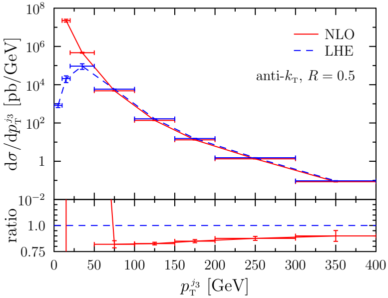
Subleading colours and spin correlations in POWHEG

Nason JHEP11(2004)040; Frixione, Nason, Oleari JHEP11(2007)070

- use $\mathrm{D}_i = \rho_i \cdot \mathrm{R}$
- trivially correct spin and colour
- separate shower for hardest emission (the one that is matched to NLO calculation)
- transition to standard shower for remainder of evolution

$\Rightarrow$ care to be taken to ensure consistent resummation

- if POWHEG based on same PS $\Rightarrow$ trivially consistent resummation



Kardos, Nason, Oleari JHEP04(2014)043

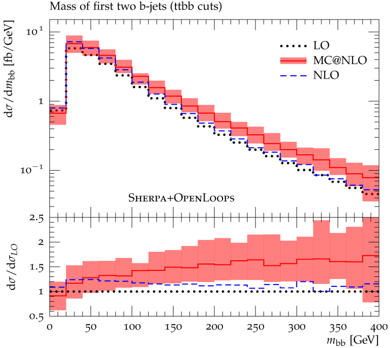
Subleading colours and spin correlations in S-MC@NLO

Höche, Krauss, MS, Siegert JHEP09(2012)049

- use $\mathrm{D}_i = \mathrm{S}_i$ (NLO subtraction terms)
- trivially correct spin and colour
- separate shower for hardest emission (the one that is matched to NLO calculation)
- transition to standard shower for remainder of evolution

$\Rightarrow$ care to be taken to ensure consistent resummation

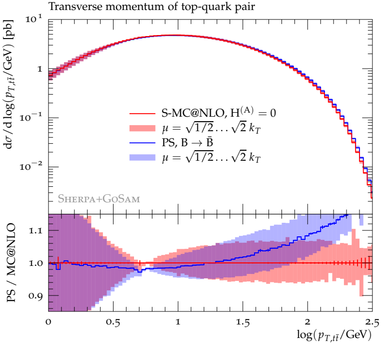
- if S-MC@NLO based on PS $\Rightarrow$ trivially consistent resummation



Cascioli et.al. arXiv:1309.5912

Subleading colours in first emission

Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)014040



Importance of
$N_c = 3$ colour coherence
(SHERPA's S-MC@NLO)
vs.
$N_c \to \infty$ colour coherence
(SHERPA's CSSHOWER++)

- small effect on standard (rapidity blind) observables, e.g. $p_{\perp,t\bar{t}}$
  $\to$ some destructive interference at large $p_{\perp,t\bar{t}}$
- large effect on $A_{FB}(p_{\perp,t\bar{t}})$
  $\to$ subleading colour dipoles decrease asymmetry

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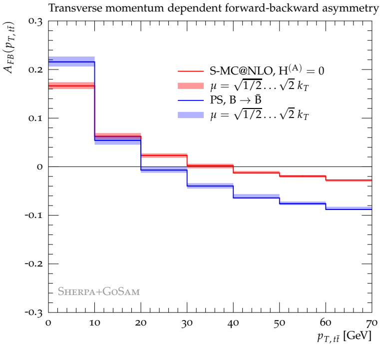

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Subleading colours in evolution

Plätzer, Sjödahl JHEP07(2012)042

- soft-collinear approximation

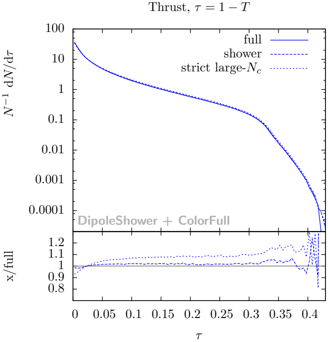
$$B_{n+1} \cong -\sum_{i,j,k} \frac{V_{ij,k}}{\mathbf{T}_{ij}^2} \langle \mathcal{M}_n | \mathbf{T}_{\widetilde{ij}} \mathbf{T}_{\widetilde{k}} | \mathcal{M}_n \rangle$$

- iterate
- subleading dipoles can have negative sign

$\Rightarrow$ known how to deal with in veto algorithm

- costly for high multiplicities

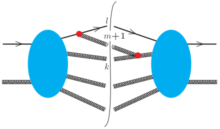
$\Rightarrow$ use for first few emissions



Subleading colours in evolution

Nagy, Soper arXiv:1401.6364

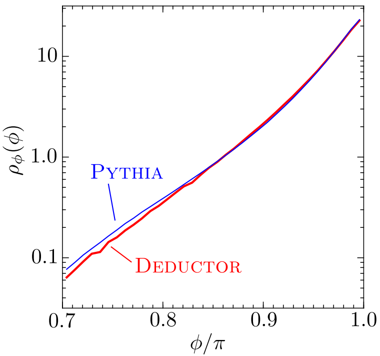
- uses splitting functions including interference



Nagy, Soper JHEP03(2008)030

→ effects beyond DGLAP $1 \to 2$ splittings

→ contributes to soft limit



⇒ see Zoltan's talk for details

Parton shower uncertainties

- assess impact of choices detailed earlier:
  - evolution scale
  - recoil scheme
  - finite terms
  - scales in $g \to q\bar{q}$
- due to unweighting and involved interplay of acception and rejection weights simple reweighting a la NLO not trivial
  $\to$ weight vector with predefined variations VINCIA
  $\to$ similar techniques as in weighted showers
- parton showers generate many terms implicitely
  $\to$ devise counterterms to keep them fixed when varying parameters

Electroweak effects – QED radiation

QED radiation off leptons

- factorises from radiation of quarks

$\Rightarrow$ can be treated by different methods, e.g. YFS as in HERWIG++ and SHERPA, or conceptually different shower, e.g. PHOTOS

QED radiation off quarks

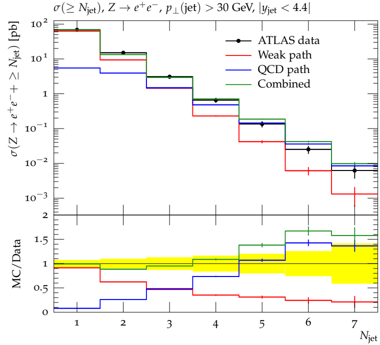
- has to be interleaved with QCD evolution
- implies same ordering
- problem in dipole showers as no large-N_c limit, no subleading dipoles $\rightarrow$ negative dipoles are not subleading

$\Rightarrow$ hard to get soft photon emissions correct

Electroweak effects in PYTHIA8

- splitting functions highly spin dependent
  $\to$ embedded in spin-avaraged shower by assuming helicity admixture
- correct first EW emission by ME reweighting
- decay W/Z at end of evolution, showering the new singlet by itself

Christiansen, Sjöstrand arXiv:1401.5238



$$\mathcal{K}^{\rm FS}_{q\to qX} = \frac{\alpha_{\rm eff}}{2\pi\, t}\,\frac{1+z^2}{1-z} \qquad \mathcal{K}^{\rm IS}_{q\to qX} = \frac{\alpha_{\rm eff}}{2\pi\, t}\,\frac{1+z^2(1+r)^2}{1-z(1+r)^2}$$

modification with $r = \frac{m_3}{m_4}$ necessary to have $\mathcal{K}_{\rm PS} > \mathcal{K}_{\rm ME}$

Electroweak effects in SHERPA

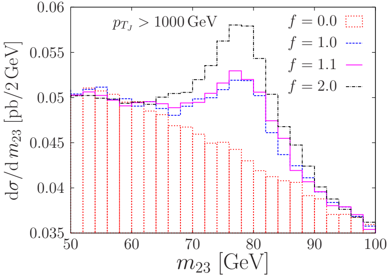
- EW splitting functions used since SHERPA-1.2.0 for clustering final state
- problem: spin-dependent $\rightarrow$ fix with proc. dep. s_{eff}

$\Rightarrow$ correct only for first EW emission

- immediately decay W, Z

$\Rightarrow$ properly embed decay product evolution

Krauss, Petrov, MS, Spannowsky arXiv:1403.4788



$$\mathcal{K}_{f(s)\to f'W(s)}(t,z) = \frac{\alpha}{2\pi}\left[f_W\, c_\perp^W\, \tilde{\mathrm{V}}^{\text{CDST}}_{f(s)\to f'b(s)}(t,z) + f_h\, c_L^W\, \frac{1}{2t}\,(1-z)\right]$$

$$\text{with } c_\perp^W = s_{\text{eff}}\,\frac{1}{2s_W^2}\,|V_{ff'}|^2 \text{ and } c_L^W = \frac{1}{2s_W^2}\,|V_{ff'}|^2\left[s_{\text{eff}}\,\frac{m_{f'}^2}{m_W^2} + (1-s_{\text{eff}})\,\frac{m_f^2}{m_W^2}\right]$$

Conclusions

- parton showers are well defined resummation tools
- complement analytical resummations as they work under different approximations
- a lot of progress in recent years, driven by mostly theoretical considerations
- many improvements have little visible impact, but necessary for matching/merging methods to work

Thank you for your attention!