Impact of the recoil scheme on the accuracy of angular-ordered parton showers

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LFC19: Strong dynamics for physics within and beyond the Standard Model at LHC and Future Colliders

Based on Bewick, S.F.R., Richardson and Seymour [arxiv:1904.11866]

Introduction: Shower Monte Carlo generators

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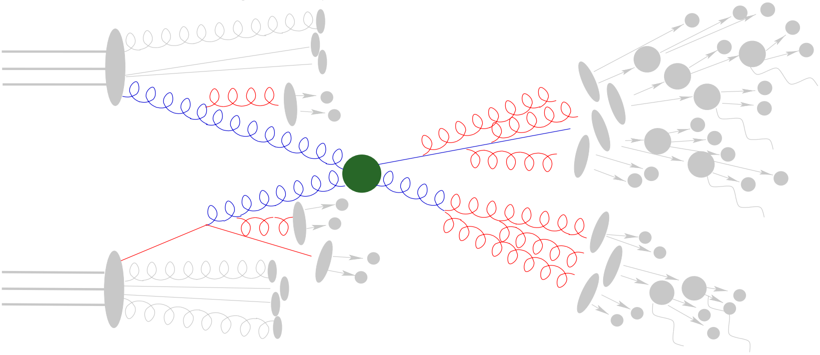

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Logharitmic accuracy of parton showers: a fixed-order study, by Dasgupta, Dreyer, Hamilton, Monni and Salam, introduced approach for assessing the logarithmic accuracy of PS algorithms based on the ability to reproduce:

1. the singularity structure of multi-parton matrix elements
2. logarithmic resummation results

Logharitmic accuracy of parton showers: a fixed-order study (I)

- Case of study: double gluon emission, well separated in rapidity, in $e^+e^- \to q\bar{q}$:

$$\boxed{dP_2 = \frac{C_F^2}{2!}\prod_{i=1}^{2}\frac{2\alpha_s(p_{T,i})}{\pi}\frac{dp_{T,i}}{p_{T,i}}d\eta_i} \qquad \text{where } \eta_i = -\log\left(\tan\left(\frac{\theta}{2}\right)\right)$$

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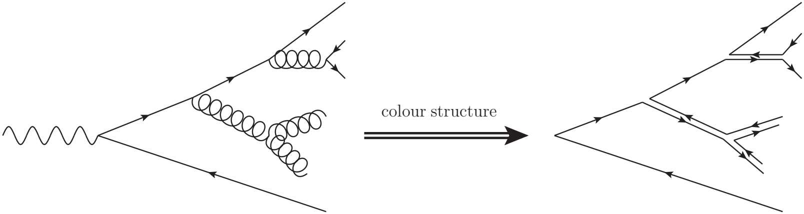
- **Dipole showers** implemented in the `Pythia8` and `Sherpa` generators were considered.



Logharitmic accuracy of parton showers: a fixed-order study (II)

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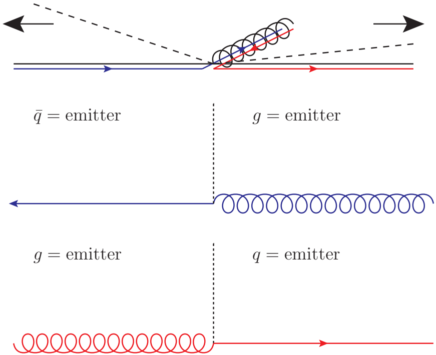

- Dipole frame: there are region where the second gluon looks closer to the first gluon
- When the gluon is identified as emitter:
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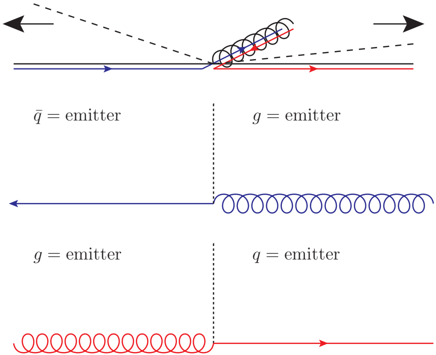

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What happens for the **angular-ordered** shower implemented in `Herwig7`??

Herwig7 angular-ordered parton shower

- The (anti-)quark is identified as **shower progenitor** and the anti-quark (quark) is its colour partner: each shower progenitor is showered independently in the frame where it is anti-collinear with the colour partner.

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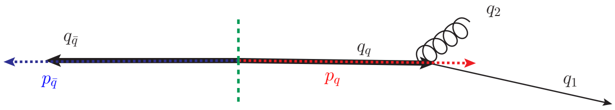
- Single emission from the quark:



$$\begin{cases} q_1 &= z p_q + \beta_1 p_{\bar{q}} + p_T \\ q_2 &= (1-z) p_q + \beta_2 p_{\bar{q}} - p_T \\ q_q &= p_q + (\beta_1 + \beta_2)\, p_{\bar{q}} \end{cases}$$

$$\tilde{q}^2 = \frac{q_q^2}{z(1-z)} = \frac{2 q_1 \cdot q_2}{z(1-z)} = \frac{p_T^2}{z^2(1-z)^2} \sim E_q^2 \theta^2$$

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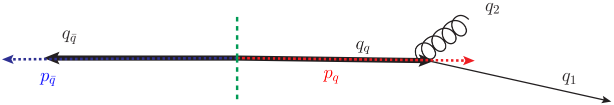

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- **Soft limit**: $1 - z \equiv \epsilon \to 0$, $\boxed{p_T \to \epsilon \tilde{q}, \quad \eta \to \log\left(\frac{Q}{\tilde{q}}\right)}$

$$dP^{\text{herwig}} \to 2C_F \frac{\alpha_s(\epsilon\tilde{q})}{\pi} \frac{d\tilde{q}}{\tilde{q}} \frac{d\epsilon}{\epsilon} = \boxed{2C_F \frac{\alpha_s(p_T)}{\pi} \frac{dp_T}{p_T} d\eta} \quad ✓$$

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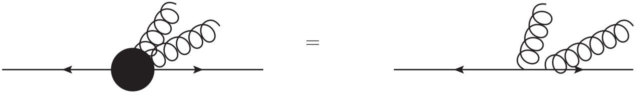
  2. $\boxed{\eta_2 > 0,\ |\eta_1 - \eta_2| \gg 1}$:

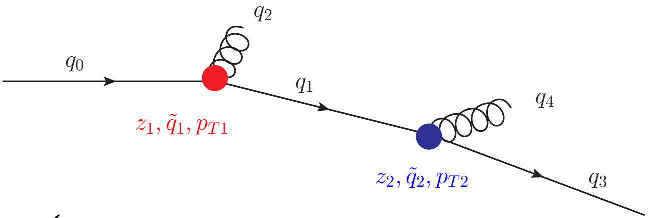


$|\eta_1 - \eta_2| \gg 1$: this suppress the gluon splitting;
angular ordering $\mathbf{z_1^2 \tilde{q}_1^2} > \mathbf{\tilde{q}_2^2}$ imposes that the one with smallest rapidity comes first;

To do

We achieve the correct **colour factor**, we need to check the **recoil**

Herwig7 angular-ordered parton shower



$$\begin{cases} q_0 &= p_q + (\beta_2 + \beta_3 + \beta_4) p_{\bar{q}} \\ q_1 &= z_1 p_q + (\beta_3 + \beta_4) p_{\bar{q}} + p_{T1} \\ q_2 &= (1 - z_1) p_q + \beta_2 p_{\bar{q}} - p_{T1} \\ q_3 &= z_2 z_1 p_q + \beta_3 p_{\bar{q}} + z_2 p_{T1} + p_{T2} \\ q_4 &= (1 - z_2) z_1 p_q + \beta_4 p_{\bar{q}} + (1 - z_2) p_{T1} - p_{T2} \end{cases}$$

$$\boxed{\mathbf{q_0^2} = \frac{\mathbf{p_{T1}^2}}{z_1(1-z_1)} + \frac{q_1^2}{z_1}} \quad \Rightarrow \quad \text{Impossible to preserve simultaneously } q_q^2 \text{ and } p_{T1}^2$$

The choice of the preserved quantity determines the **recoil scheme**

p_T-preserving scheme

The original (and simplest) choice of hep-ph/0310083 (Gieseke, Stephens and Webber) is to preserve the **transverse momentum**:

$$\tilde{q}_i^2 = \frac{p_{Ti}^2}{z_i^2(1-z_i)^2}$$

- $\boxed{p_{Ti}^2 = z_i^2(1-z_i)^2\tilde{q}_i^2 \to \epsilon_i^2\tilde{q}_i^2}$ $\quad\boxed{\eta_i \to \log\left(\frac{Q}{\tilde{q}_i}\right)}$

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- $\boxed{q_0^2 = z_1(1-z_1)\tilde{q}_1^2 + \frac{z_2(1-z_2)\tilde{q}_2^2}{z_1}}$

  $\Rightarrow$ too much hard radiation in the parton shower as there is no compensation between the transverse momentum of the branching and the virtualities of the partons produced in the branching

q^2-preserving scheme

In Ref. 1708.01491 (Reichelt, Richardson and Siodmok) the **virtuality**-preserving scheme is introduced:

$$\tilde{q}_i^2 = \frac{q_i^2}{z_i(1-z_i)}$$

- The transverse momentum of the first emission is reduced

$$\boxed{p_{T1}^2} = \max\left[0, (1-z_1)\left[z_1^2(1-z_1)\tilde{q}_1^2 - z_2(1-z_2)\tilde{q}_2^2\right]\right]$$

$$\boxed{\rightarrow \max\left[0, \epsilon_1\left[\epsilon_1\tilde{q}_1^2 - \epsilon_2\tilde{q}_2^2\right]\right]}$$

$$\boxed{\eta_1 \rightarrow \frac{1}{2}\log\left(\frac{Q^2}{\tilde{q}_1^2 - \frac{\epsilon_2}{\epsilon_1}\tilde{q}_2^2}\right)}$$

the p_T is set to 0 and the virtuality increases if the reconstruction is not possible; we need $\epsilon_2 \ll \epsilon_1$ to be sure the soft limit is ok;

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- Better description of the tail of the distributions and in general better agreement with data

Dot-product preserving scheme

In 1904.11866 we suggested something with intermediate properties

$$\tilde{q}^2 = \frac{2q_1 \cdot q_2}{z_i(1-z_i)}$$

- The transverse momentum of the first emission is reduced by subsequent emissions

$$p_{T1}^2 = (1-z_1)^2 \left[z_1^2 \tilde{q_1}^2 - \sum_{i=2}^{n} z_i(1-z_i)\tilde{q}_i^2 \right]$$

but $\tilde{q}_{i+1} < z_i \tilde{q}_i$ implied $p_{T1} > 0$ even for infinite emissions; the **double-soft** limit is correct

$$\boxed{p_{T1}^2 \to \epsilon_1^2 \left[\tilde{q}_1^2 - \epsilon_2 \tilde{q}_2^2\right] \to \epsilon_1^2 \tilde{q}_1^2}, \quad \boxed{\eta_1 \to \log\left(\frac{Q}{\tilde{q}_1}\right)}$$

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- However, the virtuality still increases ...

$$\boxed{q_0^2 = z_1(1-z_1)\tilde{q}_1^2 + z_2(1-z_2)\tilde{q}_2^2}$$

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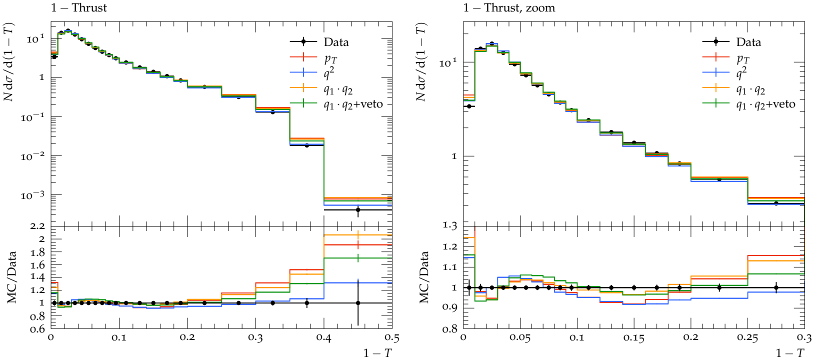
- $\lambda \approx 1$ if the emissions are all soft or collinear and is far from 1 in the hard region of the spectrum.
- We can accept the event with probability λ to improve the description of the tail of the distributions, (large virtualities) without spoiling the soft-collinear region (small virtualities).

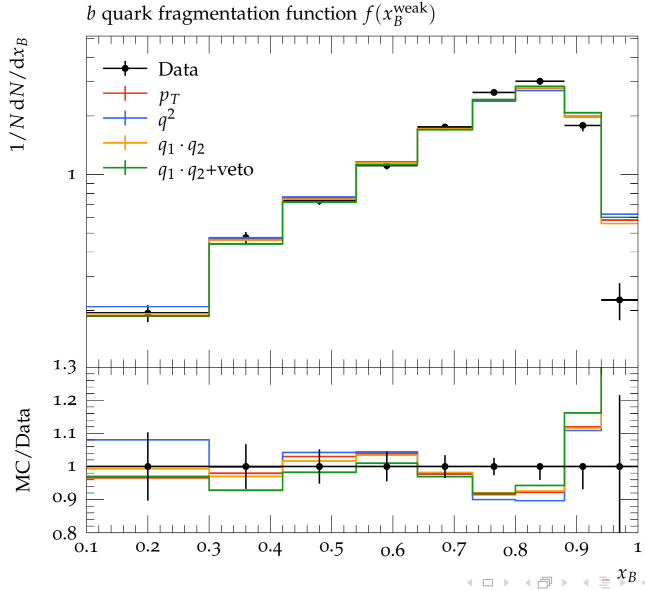
Selected LEP results

Thrust, DELPHI 1996



$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}$$

Energy distribution of weakly-decaying b hadrons from DELPHI 2011



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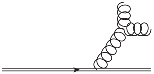
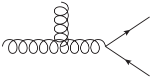
- Open issues:



  - ordering condition in case of massive recoilers: p_T can become negative also in the dot-scheme;
  - $g \to q\bar{q}$: argument of α_s and ordering condition for massive q;



  - b-quark fragmentation (does it depend on the PS or on the hadronization model?);

BACKUP

Global recoil

- Prior the shower $p_i = \{\sqrt{m_i^2 + |\vec{q}_i|}, \vec{p}_i\}$ that satisfy

$$\sum_i \sqrt{m_i^2 + |\vec{p}_i|} = \sqrt{s}, \quad \sum_i \vec{p}_i = \vec{0}.$$

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$$q_i \xrightarrow{\beta_i} q_i' = \{\sqrt{q_i^2 + \lambda^2 |\vec{p}_i|^2}, \lambda \vec{p}_i\} \quad \Rightarrow \sum_i \vec{q}_i' = \lambda \sum_i \vec{p}_i = \vec{0}$$

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If only soft-emissions take place $q_i^2 = m_i^2 + \mathcal{O}(\epsilon)$, thus this boost gives subleading contributions

Double soft-emission kinematics

Summary of Lund variables:

Preserved quantity	p_T^2	q^2	$q_1 \cdot q_2$
p_{T1}^2	$\epsilon_1^2 \tilde{q}_1^2$	$\epsilon_1 \left[\epsilon_1 \tilde{q}_1^2 - \epsilon_2 \tilde{q}_2^2\right]$	$\epsilon_1^2 \tilde{q}_1^2$
η_1	$\frac{1}{2} \log\left(\frac{Q^2}{\tilde{q}_1^2}\right)$	$\frac{1}{2} \log\left(\frac{Q^2}{\tilde{q}_1^2 - \frac{\epsilon_2}{\epsilon_1}\tilde{q}_2^2}\right)$	$\frac{1}{2} \log\left(\frac{Q^2}{\tilde{q}_1^2}\right)$
p_{T2}^2	$\epsilon_2^2 \tilde{q}_2^2$		
η_2	$\frac{1}{2} \log\left(\frac{Q^2}{\tilde{q}_2^2}\right)$		

- The kinematics of the second emission is always correct;
- The kinematic of the first emission is correct in the p_T and dot-product preserving schemes.

Double soft-emission kinematics

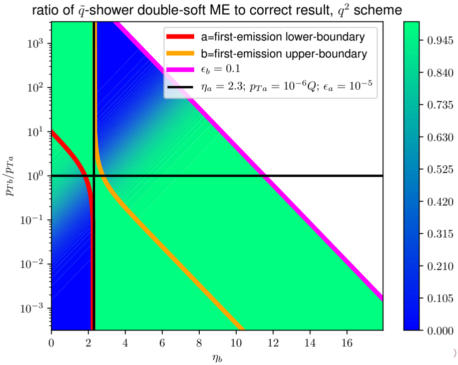
Emission of two-soft gluons with Lund variables k_{Ta}^2, η_a and k_{Tb}^2, η_b.

$$dP_2^{\text{exact}} = \frac{C_F^2}{2!}\frac{\alpha_s^2}{\pi^2}\left[\frac{dk_{Ta}^2}{k_{Ta}^2}d\eta_a\right]\left[\frac{dk_{Tb}^2}{k_{Tb}^2}d\eta_b\right]$$

$$\frac{dP_2^{\text{herwig}}}{dk_{Ta}^2\,d\eta_a\,dk_{Tb}^2\,d\eta_b} = \int \frac{C_F^2}{2!}\frac{\alpha_s^2}{\pi^2}\prod_{i=1}^{2}\left[\frac{d\tilde{q}_i^2}{\tilde{q}_i^2}\frac{d\epsilon_i}{\epsilon_i}\right]\Theta\left(\tilde{q}_1^2-\tilde{q}_2^2\right)$$
$$\times\left[\delta(\eta_1-\eta_a)\delta(k_{T1}^2-k_{Ta}^2)\delta(\eta_2-\eta_b)\delta(k_{T2}^2-k_{Tb}^2)+a\leftrightarrow b\right]$$

- The p_T^2 and $q_1\cdot q_2$ preserving schemes yield the correct double soft limit;
- For the q^2 scheme:

$$R = \frac{1}{1+\frac{k_{Tb}}{k_{Ta}}e^{\eta_a-\eta_b}}$$
$$\times\,\Theta\left(\frac{k_{Tb}}{k_{Ta}} - 2\sinh(\eta_a-\eta_b)\right)$$
$$+\,a\leftrightarrow b$$



Tuning

Each modification of the PS requires a new tuning of the hadronization parameters: interplay perturbative & non perturbative

Preserved	p_T	q^2	$q_i \cdot q_j$	$q_i \cdot q_j$+veto
Light-quark hadronization and shower parameters				
AlphaMZ ($\alpha_s^{\text{CMW}}(M_Z)$)	**0.1074**	**0.1244**	**0.1136**	**0.1186**
pTmin	0.900	1.136	0.924	0.958
ClMaxLight	4.204	3.141	3.653	3.649
ClPowLight	3.000	1.353	2.000	2.780
PSplitLight	0.914	0.831	0.935	0.899
PwtSquark	0.647	0.737	0.650	0.700
PwtDIquark	0.236	0.383	0.306	0.298
Bottom hadronization parameters				
ClMaxBottom	5.757	2.900	6.000	3.757
ClPowBottom	0.672	0.518	0.680	0.547
PSplitBottom	0.557	0.365	0.550	0.625
ClSmrBottom	0.117	0.070	0.105	0.078
SingleHadronLimitBottom	0.000	0.000	0.000	0.000
Charm hadronization parameters				
ClMaxCharm	4.204	3.564	3.796	3.950
ClPowCharm	3.000	2.089	2.235	2.559
PSplitCharm	1.060	0.928	0.990	0.994
ClSmrCharm	0.098	0.141	0.139	0.163
SingleHadronLimitCharm	0.000	0.011	0.000	0.000