Subleading colour corrections in Herwig

Johan Thorén

In collaboration with Malin Sjödahl and Simon Plätzer

Partikeldagarna, November 7, 2017

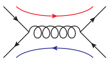
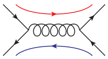
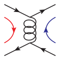
Table of contents

Section 1

Motivation

What does a standard parton shower do?

- We want to describe pp collisions at the LHC.
- Dresses the hard scattering with QCD radiation.
- Parton showers use approximations that are exact in the collinear and soft regions of emission phase space.
- Work in the $N_c \to \infty$ limit, i.e. interference terms suppressed by powers of $1/N_c$ are neglected. In the collinear limit the leading N_c approximation is exact.

$\Big|$  $\Big|^2 \propto N_c^2,$ $\quad\Big($  $\Big)\Big($  $\Big)^* \propto N_c.$

Why do subleading N_c showers?

- $1/N_c^2$ is not that small and $1/N_c$ suppression possible if there are two quark-lines.
- More energy
  - many more coloured partons.
  - many more colour suppressed terms.
- For a leading N_c shower, the number of colour connected pairs grow roughly as N_{partons}.
- The number of pairs of coloured partons grows as N^2_{partons}.
- Useful for exact next-to-leading order matching.

Section 2

Subleading N_c in dipole showers

Dipole Factorization

Dipole factorization gives, whenever i and j become collinear or one of them soft:

$$|\mathcal{M}_{n+1}(..., p_i, ..., p_j, ..., p_k, ...)|^2 =$$
$$\sum_{k \neq i,j} \frac{1}{2p_i \cdot p_j} \langle \mathcal{M}_n(p_{\tilde{ij}}, p_{\tilde{k}}, ...) | \mathbf{V}_{ij,k}(p_i, p_j, p_k) | \mathcal{M}_n(p_{\tilde{ij}}, p_{\tilde{k}}, ...) \rangle$$

An emitter $\tilde{ij}$ splits into two partons i and j, with the spectator $\tilde{k}$ absorbing the momentum to keep all partons (before and after) on-shell.
(Catani, Seymour arXiv:hep-ph/9605323)

Dipole Factorization

The (spin averaged) splitting kernel is

$$\mathbf{V}_{ij,k}(p_i,p_j,p_k) = -8\pi\alpha_s V_{ij,k}(p_i,p_j,p_k)\frac{\mathbf{T}_{\tilde{ij}}\cdot\mathbf{T}_k}{\mathbf{T}^2_{\tilde{ij}}}$$

Where, for a final-final dipole configuration, we have for example

$$V_{q\to qg,k}(p_i,p_j,p_k) = C_F\left(\frac{2(1-z)}{(1-z)^2+p_\perp^2/s_{ijk}} - (1+z)\right)$$

Emission probability

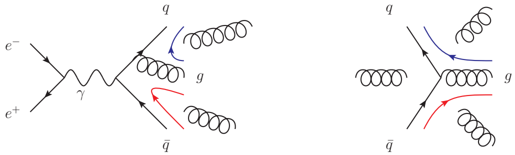
For a leading N_c shower, the emission probability would be

$$\mathrm{d}P_{ij,k}(p_\perp^2, z) = V_{ij,k}(p_\perp^2, z)\frac{\mathrm{d}\phi_{n+1}(p_\perp^2, z)}{\mathrm{d}\phi_n} \times \frac{\delta(\tilde{ij}, \tilde{k} \text{ colour connected})}{1 + \delta_{\tilde{ij}\,g}}$$

Including subleading emissions, instead gives

$$\mathrm{d}P_{ij,k}(p_\perp^2, z) = V_{ij,k}(p_\perp^2, z)\frac{\mathrm{d}\phi_{n+1}(p_\perp^2, z)}{\mathrm{d}\phi_n} \times \frac{-1}{\mathbf{T}_{\tilde{ij}}^2}\frac{\langle \mathcal{M}_n | \mathbf{T}_{\tilde{ij}} \cdot \mathbf{T}_{\tilde{k}} | \mathcal{M}_n \rangle}{|\mathcal{M}_n|^2}$$

Emission probability



- Leading N_c: qg and $\bar{q}g$ can radiate coherently.
- Subleading N_c: $q\bar{q}$ can also radiate coherently, but suppressed by a colour factor.

Overall picture

Using Herwigs dipole shower

- Instead of only colour connected emitter-spectator pairs radiating, all possible pairs can radiate.
- The emission probabilities are modified by a factor

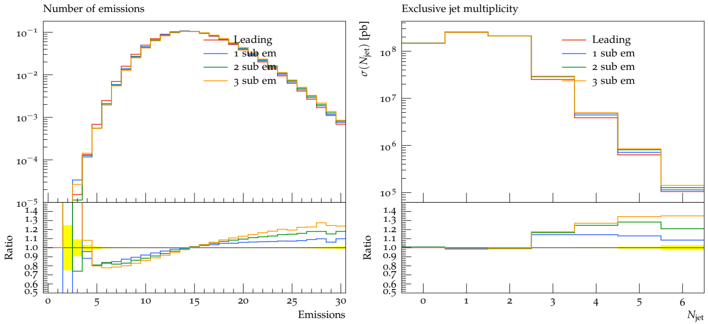
$$\omega_{ik}^{n} = \frac{-1}{\mathbf{T}_{\tilde{ij}}^{2}} \frac{\langle \mathcal{M}_n | \mathbf{T}_{\tilde{ij}} \cdot \mathbf{T}_{\tilde{k}} | \mathcal{M}_n \rangle}{|\mathcal{M}_n|^2}$$

  which is included using the reweighting in Herwig.
- We evolve the colour structure to be able to evaluate the factor above for the next emission.
- Continue for a set number of emissions and then do the rest with the standard shower.

Section 3

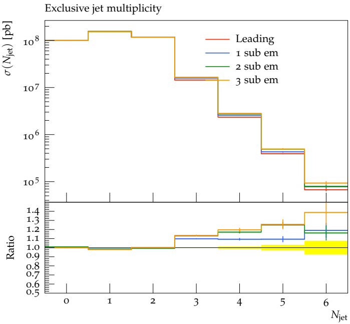
Preliminary results

Preliminary $pp \to jj$ results

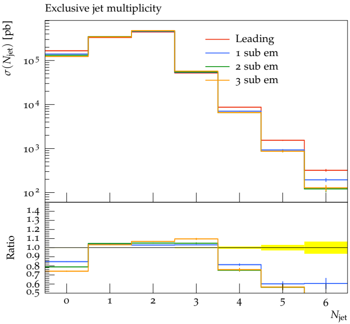


- Jet cut: $p_{\perp\,\mathrm{cut}} = 20\,\mathrm{GeV}$

Jet multiplicity for $pp \to jj$ subprocesses



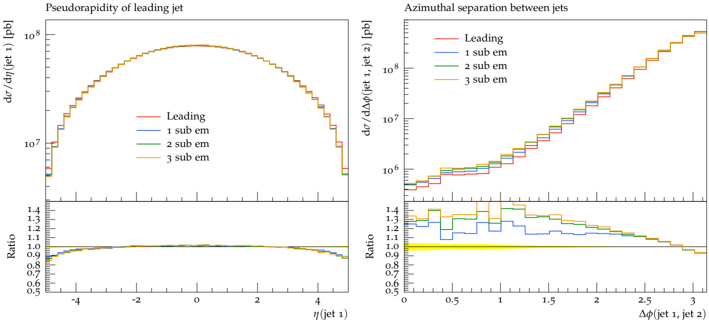
(a) $gg \to gg$



(b) $uu \to uu$

- Jet cut: $p_{\perp\,\text{cut}} = 20$ GeV.
- Difference as compared to the leading shower can be in different directions.

Pseudorapidity and $\Delta\phi_{12}$



- So far we have mainly been looking at standard QCD observables for pp, it should not be hard to find observables with sizable corrections of order $1/N_c$.

Section 4

Conclusions and outlook

Conclusions

Conclusions:

- Subleading colour corrections can have sizable effects on standard QCD observables.

Work in progress:

- Look at more processes.
- Look at the effect on analyses with data.
- Look for observables where subleading N_c has a large effect (found for e^+e^- collisions in (Platzer, Sjodahl, arXiv:1206.0180)).

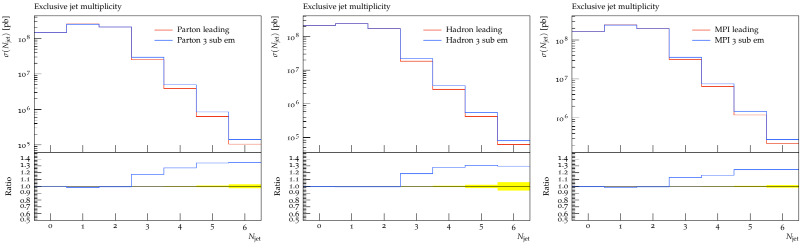
Future work:

- Tuning, virtual corrections, updated hadronization model.

Section 5

Extra slides

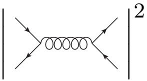
How about hadronization and MPI?



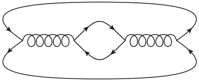
- The effects of the subleading emissions are not washed out by either hadronization or MPI.

Example of $1/N_c$ suppressed terms

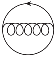
Leading colour structure:



$$^2 =$$



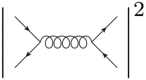
$$= T_R$$



$$= T_R^2(N_c^2 - 1) \propto N_c^2.$$

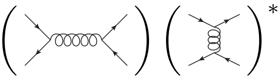
Example of $1/N_c$ suppressed terms

Leading colour structure:

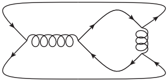


$$\propto N_c^2.$$

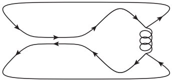
Interference term:



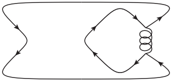
$$=$$



$$= T_R$$

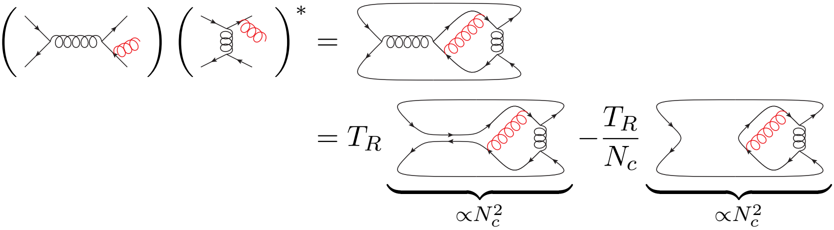


$$- \frac{T_R}{N_c}$$



$$= 0 - T_R^2 \frac{N_c^2 - 1}{N_c} \propto N_c.$$

Example of $1/N_c$ suppressed terms



Density operator

Evaluating the first colour matrix element corrections, ω_{ik}^{n}, after the hard process is straightforward as the amplitude $|\mathcal{M}_n\rangle$ has been calculated. For the next emission we need $|\mathcal{M}_{n+1}\rangle$.
We can write the amplitude as a vector in some basis (trace, multiplet, etc.),

$$|\mathcal{M}_n\rangle = \sum_{\alpha=1}^{d_n} c_{n,\alpha}|\alpha_n\rangle \leftrightarrow \mathcal{M}_n = (c_{n,1}, \ldots, c_{n,d_n})^T$$

Observe that

$$|\mathcal{M}_n|^2 = \mathcal{M}_n^\dagger S_n \mathcal{M}_n = \mathrm{Tr}\left(S_n \times \mathcal{M}_n \mathcal{M}_n^\dagger\right)$$

and

$$\langle \mathcal{M}_n|\mathbf{T}_{\tilde{i}\tilde{j}} \cdot \mathbf{T}_{\tilde{k}}|\mathcal{M}_n\rangle = \mathrm{Tr}\left(S_{n+1} \times T_{\tilde{k},n}\mathcal{M}_n \mathcal{M}_n^\dagger T_{\tilde{i}\tilde{j},n}^\dagger\right)$$

Density operator

We construct an "amplitude matrix" $M_n = \mathcal{M}_n \mathcal{M}_n^\dagger$, that we evolve by

$$M_{n+1} = -\sum_{i \neq j} \sum_{k \neq i,j} \frac{4\pi\alpha_s}{p_i \cdot p_j} \frac{V_{ij,k}(p_i, p_j, p_k)}{\mathbf{T}^2_{\tilde{ij}}} T_{\tilde{k},n} M_n T^\dagger_{\tilde{ij},n}$$

where

$$V_{ij,k} = \mathbf{T}^2_{\tilde{ij}} \frac{p_i \cdot p_k}{p_j \cdot p_k}.$$

This allows us to calculate the "colour matrix element corrections".

Colour matrix element correction

With a way to evolve the density operator we can calculate the colour matrix element corrections for any number of emissions

$$\omega_{ik}^{n} = \frac{-1}{\mathbf{T}_{\tilde{ij}}^{2}} \frac{\mathrm{Tr}\left(S_{n+1} \times T_{\tilde{k},n} M_n T_{\tilde{ij},n}^{\dagger}\right)}{\mathrm{Tr}\left(S_n \times M_n\right)}$$

- ω_{ik}^{n} can be negative, this is included through the weighted Sudakov algorithm (Bellm, J. et. al. arXiv:1605.08256).