Future Prospects for Parton Showers

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$*$ See white paper for 130 references.

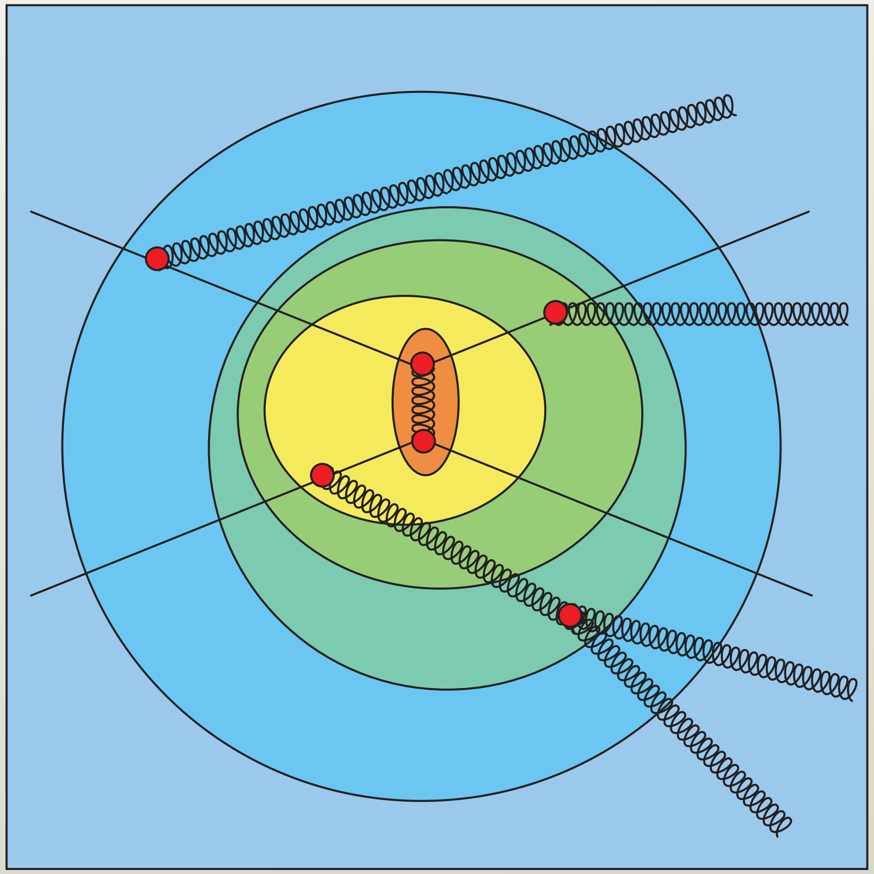
Review of parton showers

- Based on factorization of cross sections:

$$\frac{d\sigma}{dy} = \sum_{a,b} \int_{x_A}^{1} d\xi_A \int_{x_B}^{1} d\xi_B \; f_{a/A}(\xi_A,\mu) \; f_{b/B}(\xi_B,\mu) \; \frac{d\hat{\sigma}_{ab}(\mu)}{dy} + \mathcal{O}(m/M)$$

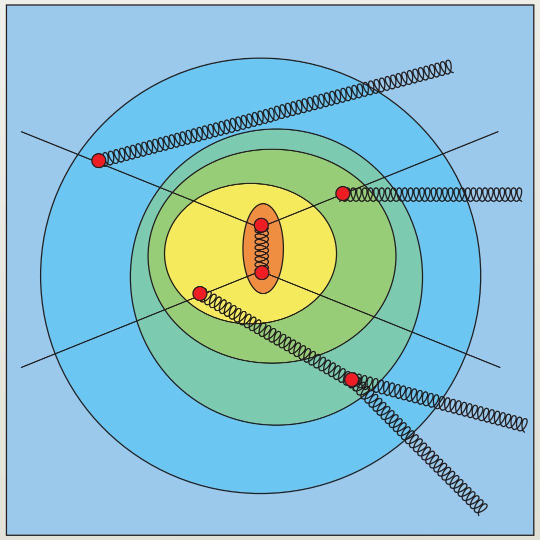
- Shower generates an approximation to the perturbative cross section at very high order.

- This uses the renormalization group.



- The approximation starts with the hardest part of the cross section and works toward softer parts.

Matching

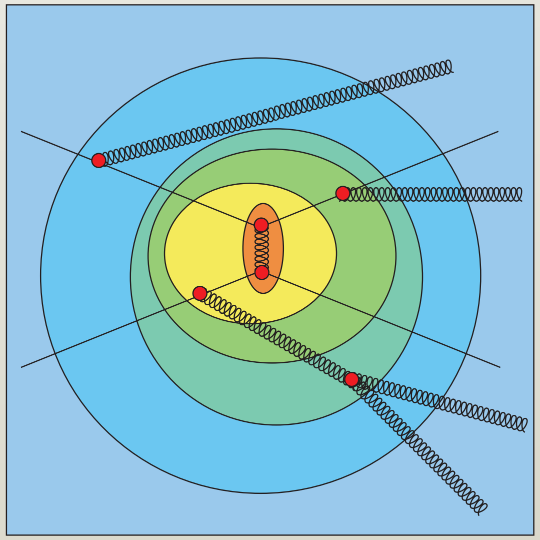


- From Born matrix elements, the shower generates approximate corrections of order α_s, α_s^2, ...
- Suppose that we have *exact* perturbative corrections of order α_s, or even α_s and α_s^2.
- Then we need to correct the shower generated contributions.
- This is called *matching*.
- This has been the subject of a large effort in recent years.
- This effort continues.

Merging

- One can also try to match to two processes at once.

- Say $p + p \to \text{Higgs} + X$
  and $p + p \to \text{Higgs} + \text{Jet} + X$.



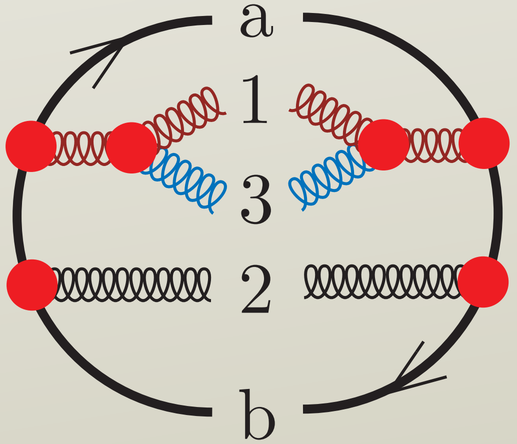
- This is called *merging*.

- Merging requires definitions to differentiate the processes.

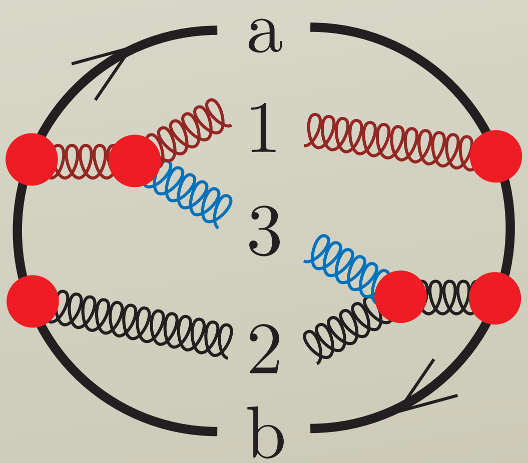
- Again, a lot of work has gone into this
  and continues to go into this.

Quantum interference

- Parton showers need to follow quantum mechanics.
- Typically they explicitly include quantum interference.
- A picture for a splitting amplitude squared:



- An interference diagram:



- First order showers like this are called *dipole* showers.

Spin

- Partons carry quantum spin.
- We need to account for the evolution of the spin density matrix $\big|\{s\}_m\big\rangle\big\langle\{s'\}_m\big|$.
- There is a nice algorithm for this due to Collins and Knowles.
- This is implemented in Herwig.
- There is further work to be done, but it is progressing.

Color

- Partons carry quantum color.
- We need to account for the evolution of the color density matrix $\big|\{c\}_m\big\rangle\big\langle\{c'\}_m\big|$.
- Mostly programs use the *leading color* approximation.
- There has been extensive recent work that studies color density matrix evolution resulting from both real emission graphs and virtual exchange graphs.
- My personal choice is to use the "LC+" approximation.

Large logarithms

- Many important cross sections depend on two very different momentum scales.
- They then contain logarithms L of the ratio of the scales.
- One wants to sum terms of the form $\alpha_{\mathrm{s}}^{n} L^{m}$.
- This is often done using an analytical formula.
- In some cases a parton shower does a good job with this.
- This issue is the subject of intense current study.

Threshold logarithms

- There are also large logarithms known as *threshold logarithms*.
- These are important when parton momentum fractions x are large.
- There is a large literature with analytic formulas for summing them.
- One parton shower algorithm sums them.
- Matching to NLO or NNLO perturbative calculations can help.

Electroweak radiation

- For the LHC or for future colliders, it would be good to include electroweak radiation in a parton shower.
- This is a challenge:
  - The nature of the theory changes between very large scales and smaller scales because the SU(2) gauge theory is spontaneously broken.
  - Protons and electrons are not singlets under the SU(2)$\times$U(1) gauge group.
- There has been substantial work to address these issues.

NLO shower

- The parton splitting operators in current parton showers are just order α_s.

- It is an important goal to construct a parton shower with splitting operators at order order α_s^2.

- This is roughly equivalent to constructing infrared subtractions for a NNLO perturbative calculation.

- Constructing an NLO shower is a goal for the future, but there has been recent progress in this direction.