Dijet Production with CoLoRFuLNNLO

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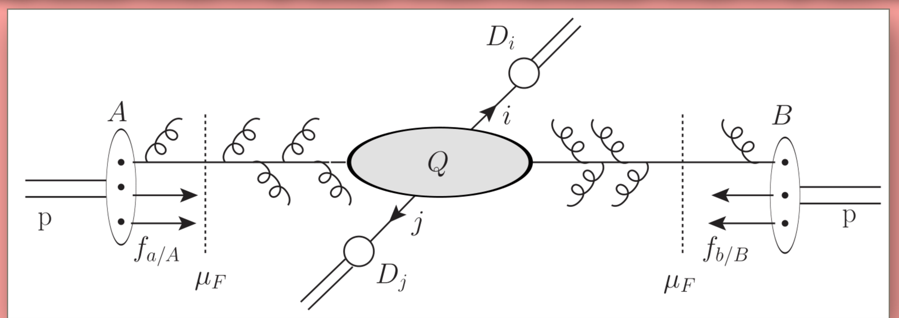
Introduction

- Multiloop amplitudes are important for obtaining higher-order predictions, hence they are essential in making precise predictions.
- Several advances were made in computing multiloop amplitudes. New techniques and tools [1-3] foreshadow automated next-to-next-to-leading order (NNLO) calculations and beyond.
- Another major bottleneck of higher-order calculations is the treatment of unresolved emissions. For regularization various slicing and subtraction methods [4-11] exist.
- At NNLO the ultimate testing ground for a method is the computation of dijet production at hadron colliders.
- Dijet production is important for Standard Model measurements and for new physics searches.
- Dijet production is also important for Parton Distribution Function (PDF) fits.

Factorization theorem



For an IR-safe jet observable J computed in a hadron-initiated process the cross section is:

$$\sigma[J](p_A,p_B) = \sum_{a,b}\int_0^1 dx_a dx_b f_{a/A}(x_a;\mu_F^2) f_{b/B}(x_b;\mu_F^2)\sigma_{ab}[J](p_a p_b;\mu_F^2)$$

p_A and p_B are the momenta of incoming hadrons, x_a and x_b are Bjorken's xs, $f_{a/A}$ and $f_{b/B}$ are the PDFs, μ_F is the factorization scale and σ_{ab} is the partonic cross section defined with partons a and b as incoming with $p_a = x_a p_A$ and $p_b = x_b p_B$.

Partonic cross sections up to NNLO

The partonic cross section has the perturbative expansion in terms of α_S:

$$\sigma_{ab}[J] = \sigma_{ab}^{LO}[J] + \sigma_{ab}^{NLO}[J] + \sigma_{ab}^{NNLO}[J] + \ldots$$

where $\sigma_{ab}^{\mathrm{LO}}[J]$, $\sigma_{ab}^{\mathrm{NLO}}[J]$ and $\sigma_{ab}^{\mathrm{NNLO}}[J]$ represent the contributions at different orders in α_S. Having m partons in the final state at lowest order it can be written as:

$$\sigma_{ab}^{LO}[J] = \int_m d\sigma_{ab}^{B} J_m$$

where $d\sigma_{ab}^{\mathrm{B}}$ is the fully differential Born cross section with a and b as initial state partons.

The NLO contribution is the sum of two terms:

$$\sigma_{ab}^{NLO}[J] = \int_{m+1} d\sigma_{ab}^{R} J_{m+1} + \int_m \{d\sigma_{ab}^{V} + d\sigma_{ab}^{C}\} J_m.$$

Here $d\sigma_{ab}^{\mathrm{R}}$ stands for the real-emission contribution, $d\sigma_{ab}^{\mathrm{V}}$ is the one-loop term and $d\sigma_{ab}^{\mathrm{C}}$ is the collinear counterterm.

$$\sigma_{ab}^{NNLO}[J] = \int_{m+2} d\sigma_{ab}^{RR} J_{m+2} + \int_{m+1}\{d\sigma_{ab}^{RV} + d\sigma_{ab}^{C_1}\} J_{m+1} + \int_m \{d\sigma_{ab}^{VV} + d\sigma_{ab}^{C_2}\} J_m$$

where $d\sigma_{ab}^{\mathrm{RR}}$, $d\sigma_{ab}^{\mathrm{RV}}$ and $d\sigma_{ab}^{\mathrm{VV}}$ are the double-real, real-virtual and double-virtual contributions.These contain two extra real partons, one extra parton with one loop and two loops as compared to the Born process. $d\sigma_{ab}^{\mathrm{C_1}}$ and $d\sigma_{ab}^{\mathrm{C_2}}$ are the collinear counterterms.

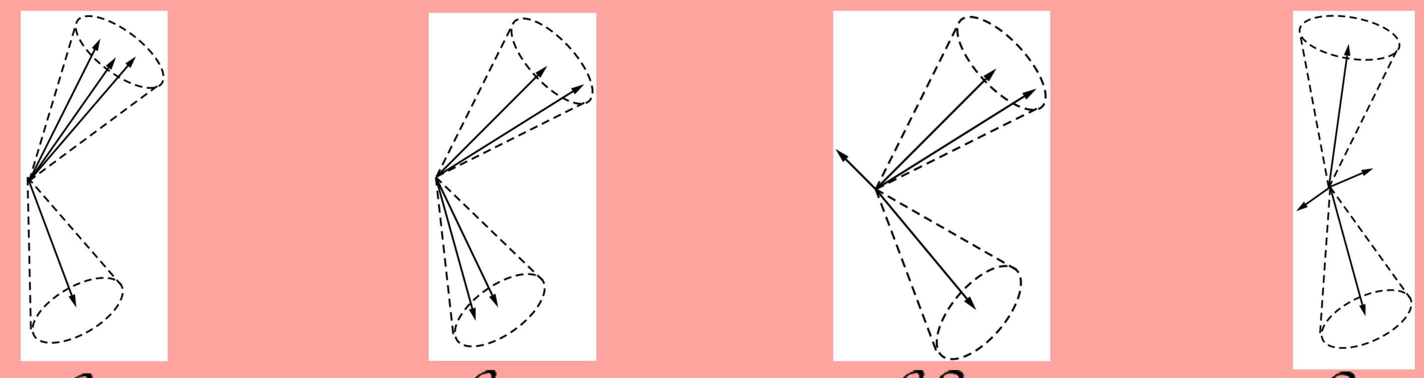
Unresolved emissions at NNLO

In the CoLoRFuLNNLO method [11] local subtraction terms are defined to regularize kinematic singularities coming from unresolved emissions possible at NNLO. These terms are obtained from factorization properties of QCD amplitudes.

At NNLO the possible doubly unresolved emissions can be:

Triple Collinear | Double Collinear | Collinear - Soft | Double Soft

Corresponding subtraction terms:



$\mathcal{C}_{irs}$ | $\mathcal{C}_{ir;js}$ | $\mathcal{CS}_{ir;s}$ | $\mathcal{S}_{rs}$

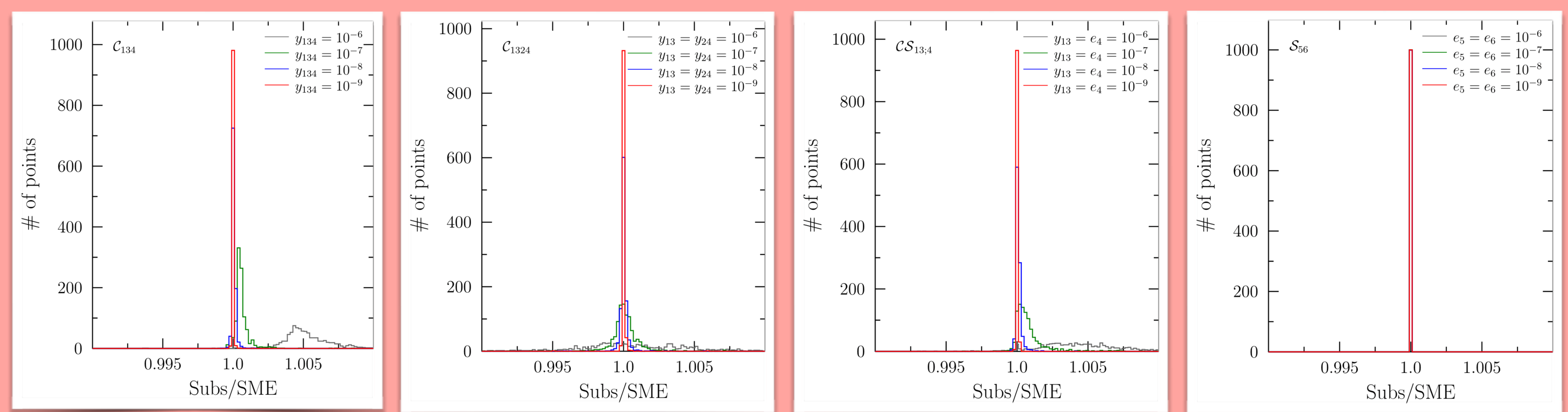
The A_2 term

- At NNLO there are three types of subtractions. The A_1-type subtraction terms for singly unresolved emissions, A_2-type ones for doubly unresolved emissions, and the A_{12}-type terms regularize the ordered singularities of A_1 and A_2.
- The A_2 subtractions are the most complicated. These use a complicated set of Sudakov parametrizations and phase-space mappings.
- In dijet production the most complicated subprocess is the purely gluonic one. Defining A_2 for this contribution is crucial both for obtaining the NNLO QCD prediction for dijet production and for testing the generality of the method.
- The full A_2 is:

$$\begin{aligned}
\mathcal{A}_2|\mathcal{M}_{m+2}^{(0)}|^2 = \sum_{r,s\in F}\Bigg\{\sum_{a\in I}\Bigg[&\frac{1}{2}\mathcal{C}_{ars} + \sum_{\substack{b\in I\\ b\neq a}}\frac{1}{2}\mathcal{C}_{ar;bs} + \sum_{\substack{j\in F\\ j\neq r,s}}\frac{1}{2}\mathcal{C}_{ar;js} + \\
&+\mathcal{CS}_{ar;s} - \mathcal{C}_{ars}\mathcal{CS}_{ar;s} - \sum_{\substack{j\in F\\ j\neq r,s}}\mathcal{C}_{ar;js}\mathcal{CS}_{ar;s} - \sum_{\substack{j\in F\\ j\neq r,s}}\frac{1}{2}\mathcal{C}_{jr;as}\mathcal{CS}_{jr;s} - \sum_{\substack{b\in I\\ b\neq a}}\mathcal{C}_{ar;bs}\mathcal{CS}_{ar;s} - \\
&-\mathcal{CS}_{ar;s}\mathcal{S}_{rs} - \frac{1}{2}\mathcal{C}_{ars}\mathcal{S}_{rs} + \mathcal{C}_{ars}\mathcal{CS}_{ar;s}\mathcal{S}_{rs} + \frac{1}{2}\Bigg(\sum_{\substack{b\in I\\ b\neq a}}\mathcal{C}_{ar;bs}\mathcal{S}_{rs} + \sum_{\substack{j\in F\\ j\neq r,s}}\mathcal{C}_{ar;js}\mathcal{S}_{rs}\Bigg)\Bigg] + \\
&+\sum_{\substack{i\in F\\ i\neq r,s}}\Bigg[\frac{1}{6}\mathcal{C}_{irs} + \sum_{\substack{j\in F\\ j\neq i,r,s}}\frac{1}{8}\mathcal{C}_{ir;js} + \frac{1}{2}\Bigg(\mathcal{CS}_{ir;s} - \mathcal{C}_{irs}\mathcal{CS}_{ir;s} - \sum_{\substack{j\in F\\ j\neq i,r,s}}\mathcal{C}_{ir;js}\mathcal{CS}_{ir;s}\Bigg) - \\
&-\mathcal{CS}_{ir;s}\mathcal{S}_{rs} - \frac{1}{2}\mathcal{C}_{irs}\mathcal{S}_{rs} + \mathcal{C}_{irs}\mathcal{CS}_{ir;s}\mathcal{S}_{rs} + \sum_{\substack{j\in F\\ j\neq i,r,s}}\frac{1}{2}\mathcal{C}_{ir;js}\mathcal{S}_{rs}\Bigg] + \frac{1}{2}\mathcal{S}_{rs}\Bigg\}
\end{aligned}$$

Checking the limiting behavior

- The A_2 terms regularize the double-real squared matrix element in all doubly unresolved limits.
- Possible overlaps between A_2 singularities are cancelled among the various A_2 terms.
- One way of testing cancellation is generating phase space points with given softness and/or collinearity and histograming the ratio between the full A_2 and the double-real squared matrix element.



Conclusions - Outlook

- We defined the A_2 subtractions which regularize the double-real square matrix element in all possible doubly unresolved limits.
- We checked the A_2 terms for the purely gluonic contribution to dijet production.
- To regularize the double-real squared matrix element in all possible limits the A_{12} terms are needed to be implemented.
- To make predictions for dijet production at the LHC we have to implement all the other subprocesses as well.

MCCSM

- The calculation was performed in the MCCSM (Monte Carlo for the CoLoRFuLNNLO Subtraction Method) numerical framework [12].
- MCCSM is a highly flexible, user-friendly fortran90 program library.
- The only user input is the various matrix elements.
- For LHC processes any third party PDF library can be easily used.

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