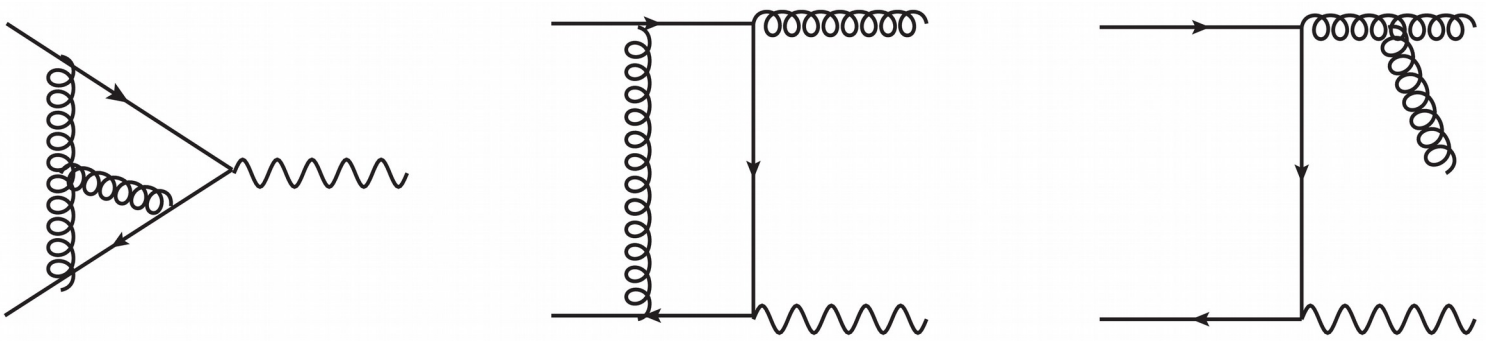
Les Houches Workshop 2019

Progress in Subtraction Methods

Introduction

- NNLO corrections:



Double virtual (VV) Real virtual (RV) Double real (RR)

- VV, RV and RR separately IR divergent due to soft and collinear radiation.
- Divergences occur in different multiplicity phase space.
- Fully differential results: need method of extracting divergences without integrating over full phase space of radiated parton, and then cancelling them to get a finite result.

  ➡Subtraction scheme

- Nontrivial at NNLO due to convoluted singularity structure in RR.

Slicing and Subtractions

- SLICING:
  - identify an observable that is sensitive to IR radiation;
  - use it to slice up the phase space into an unresolved part and a (partially) resolved part

$$\int |\mathcal{M}|^2 F_J d\phi_d = \int_0^\delta \left[|\mathcal{M}|^2 F_J d\phi_d\right]_{\text{s.c.}} + \int_\delta^1 |\mathcal{M}_J|^2 F_J d\phi_4 + \mathcal{O}(\delta)$$

  Observables:
  - qT [Catani, Grazzini '07] -- Talk by J. Mazzitelli
  - N-jettiness [Gaunt *et al* '15; Boughezal *et al* '15] – Talk by F. Tackmann

- SUBTRACTION:
  - Identify a function *S* which:
    - Reproduces the matrix elements in the unresolved limits;
    - Is (relatively) simple and can be integrated over the unresolved phase space.
  - Subtract and add back:

$$\int |\mathcal{M}|^2 F_J d\phi_d = \int \left(|\mathcal{M}_J|^2 F_J - S\right) d\phi_4 + \int S d\phi_d$$

Subtraction Methods at NNLO

Mature, all-purpose subtractions for LHC:

- Antenna [Gehrmann-de Ridder, Gehrmann, Glover '05, …] -- Talk by X. Chen
- STRIPPER [Czakon '10, '11]
  - Partition phase space (cf. FKS), then use sector decomposition to further split up phase space.
  - Parametrize in terms of energies and angles in each sector.
  - Subtract all singularities in each sector, as in FKS.
  - Local, very general, can handle massive partons.
  - Used extensively esp. for top phenomenology.

Subtraction Methods at NNLO

Specialized subtraction scheme:

- Projection-to-Born [Cacciari *et al* '15]
  - Fully local & analytic.
  - Requires the NNLO corrections differential in Born phase space (but inclusive over QCD radiation).
  - Very limited applicability (VBF, DIS, ...)
  - Offers a path to extend to N3LO for these processes.
  - See talk by X. Chen.

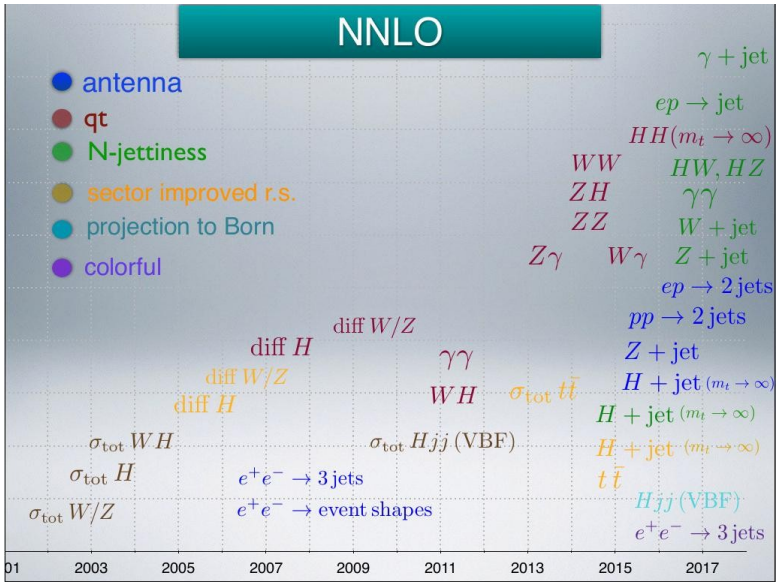
Subtraction Methods at NNLO

Under construction:

- CoLoRFulNNLO [Somogyi, Trócsányi, Del Duca '05, …].
  - Local.
  - Semi-numerical at the moment.
  - General in principle, only developed for e+e- so far.
  - Extensions to partonic initial states underways.
- Nested soft-collinear [Caola, Melnikov, R.R. '17, '19, ...] -- Talk by RR
- Local analytic sector [Magnea *et al* '18]
  - Combine FKS partitioning and CS parametrization of phase space.
  - Local, analytic.
  - Only developed for nf terms in e+e-->qqb decay.
  - Further developments underway.
- Geometric [Herzog '18]
  - Construct local slicing scheme in sij space and promote it to local subtraction scheme.
  - Very simple counterterms.
  - Proof-of-concept: reproduced pole structure of H->gg (nf=0).

Onwards & Upwards

- Subtractions at NNLO highly non-trivial due to convoluted singularity structure.
- Bottleneck for 2->2 processes at NNLO for many years.
- In last ~ 5 years, several methods have reached maturity allowing a flood of NNLO results for 2->2 processes -- “the NNLO Revolution”.
- Lots of great physics!



G. Heinrich

Buoyed by this success, we can look to the future:

- More legs – i.e. 2->3 processes
- Next order in perturbative QCD – i.e. N3LO.

Onwards & Upwards

- For some years, the bottleneck for 2->3 processes has been the two-loop amplitudes.
- Recent progress on two-loop 5 parton amplitudes indicates that these amplitudes are now in sight.

  [Abreu, Badger, Brønnum-Hansen, Chicherin, Dormans, Febres Cordero, Gehrmann, Hartanto, Heinrich, Henn, Ita, Peraro, Page, Sotnikov, Wasser, Zhang, Zola, '18, '19]

- Are subtraction schemes ready?
  - To what extent can each subtraction method use these new results to produce fully differential NNLO results for a 2->3 process, e.g. trijet production?
  - What does each method need to do to get there?
  - Caveat: can we still use one-loop providers to get stable results for the one-loop 2 -> 4 amplitudes very close to singular configurations?