NLO/MC tools

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The full picture

Proton
Parton distribution function

Hard scattering (perturbative)

Parton shower
(still perturbative)

Hadronization
(non-perturbative)

Hadron-decay

Beam remnants

Multi-parton interactions

+ many protons in one bunch
→ more than one p-p interaction
The full picture

Partonic hard scattering
- Fixed order expansion

\[ \sigma = \sigma_0 (1 + c_1 \alpha_s + c_2 \alpha_s^2 + \ldots) \]

Parton shower / Hadronization
Event generation

Resummation

\[ \alpha_s \ln (Q/Q_T) \sim 1 \]
Higher order corrections mandatory for reliable corrections

Example: Higgs production in gluon fusion

- Large corrections from higher orders
- Strong dependence on ren./fac. Scale
- Unreliable estimation of theoretical uncertainties

Many relevant LHC processes yield NLO QCD corrections ~10-100%

Need precise predictions to confirm/disprove SM!
The structure of NLO

\[ \sigma_{NLO} = \int_n (d\sigma^B + d\sigma^V + \int_1 d\sigma^A) + \int_{n+1} (d\sigma^R - d\sigma^A) \]

Subtraction terms: Needed to cancel infrared singularities numerically. Idea: Add zero in suitable way to cancel infrared singularities from real emission.
Automating NLO corrections

Increasing complexity required development of automated software tools for **numerical** calculations

Development of tools for NLO calculations (QCD)
Main bottleneck: **Virtual one-loop contribution**

- it saves time
- avoids human mistakes
- allows to reuse building blocks
- easier to handle for the user
- not necessary to understand all details
- multipurpose

Selection of excellent tools for different ingredients of one-loop calculations available

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Pheno 2016  NLO/MC tools, Nicolas Greiner
Unique basis of scalar **boxes, triangles, bubbles** and **tadpoles**, all master integrals known analytically

Reduction of tensor integrals to scalar integrals

Reduction at the integral level (Passarino-Veltman) (analytical or numerical)

Reduction on the integrand level (suited for numerical approach)

Collier [Denner, Dittmaier, Hofer]
Golem95 [Binoth et al]
PJFry [Ellis, Giele, Kunszt, Melnikov]
Ossola, Papadopulos, Pittau]

[Passarino, Veltman]
[Denner, Dittmaier]
[Binoth et al]
Integrand reduction

Integrand:  \[ A(\vec{q}) = \frac{N(q)}{D_0 D_1 \cdots D_{m-1}} \]

\[
N(q) = \sum_{i_0 < i_1 < i_2 < i_3} [d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3)] \prod_{i \neq i_0, i_1, i_2} D_i + \sum_{i_0 < i_1 < i_2} [c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2)] \prod_{i \neq i_0, i_1, i_2} D_i
\]

\[
+ \sum_{i_0 < i_1} [b(i_0 i_1) + \tilde{b}(q; i_0 i_1)] \prod_{i \neq i_0, i_1} D_i + \sum_{i_0} [\tilde{a}(i_0) + \tilde{a}(q; i_0)] \prod_{i \neq i_0} D_i
\]

\(\tilde{a}, \tilde{b}, \tilde{c}, \tilde{d}\) spurious terms, vanish upon integration, parametric form known

- **Coefficients** can be obtained by applying **suitable cuts** (i.e. setting propagators on-shell) [Cutkosky][Bern, Dixon, Dunbar, Kosower], [Britto, Cachazo, Feng]
- **Process independent** form, but **process dependent** coefficients
- **Polynomial fitting** allows to determine all coefficients
- Only need to evaluate **numerator function** \(N(q)\) on the cuts [Ossola, Papadopoulos, Pittau], [Ellis, Giele, Kunszt, Melnikov]

-> **Suitable for algorithmic, numerical implementation**
   - **Cuttools** [Ossola, Papadopoulos, Pittau], **Samurai** [Mastrolia, Ossola, Reiter, Tramontano],
   - **Ninja** [Mastrolia, Mirabella, Ossola, Peraro], **many in-house solutions...**
Both version of reduction yield fast and stable results

Remaining scalar integrals can be evaluated using integral libraries (e.g. QCDLoop [Ellis, Zanderighi], OneLoop [vanHameren])

Note: Reduction does not care how integrand is provided
-> Both unitarity inspired methods as well as Feynman diagrammatic approach has been proven to be successful in challenging applications

Healthy diversity in available tools using different methods: unitarity methods, Feynman diagrams, recursion relations, algebraic approach, numerical approach
Various general purpose tools like: BlackHat, GoSam, Helac-NLO, Madgraph5_aMC@NLO, Njet, OpenLoops, Recola...

Tools based on process list: MCFM, VBFNLO,...

Analytical tools: Feynarts, FormCalc, Looptools,...
Infrared structure of amplitude is **universal** and **process independent**

Construct terms that are simpler as real emission ME with the correct IR limit

\[ \int_{n+1}^{\infty} (d\sigma^R - d\sigma^A) \] finite !, \[ \int_1 d\sigma^A \] Has to be calculated analytically (IR divergencies cancel against virtuals)

**Phase space slicing**
Divide PS in singular/nonsingular regions, replace ME in sing region.

- **Residue subtraction (FKS)** [Frixione,Kunszt,Signer]
  -> MadFKS

- **Dipole formalism** [Catani,Seymour][Catani,Dittmaier,Seymour,Trocsanyi]
  -> Amegic++,AutoDipole, Helac-Phegas, Herwig++, MadDipole

- **Antenna subtraction** [Kosower][Daleo et al][Gehrmann et al]
Interface via Binoth-Les-Houches-Accord (BLHA)

- Step 1: MC writes an **order file**
  
  ```
  CorrectionType QCD
  AmplitudeType Loop
  2 -2 -> 1 -1
  2 -2 -> 2 -2
  ```

- Step 2: OLP writes a **contract file**
  
  ```
  CorrectionType QCD | OK
  AmplitudeType Loop | OK
  2 -2 -> 1 -1 | 0
  2 -2 -> 2 -2 | 1
  ```

- Virtual amplitude called from within the MC during runtime
  (Sherpa,Powheg,Herwig++, MG5_aMC@NLO,Whizard,...)
General purpose event generators:
• Combine ME’s, PS, hadronization and soft underlying physics in one simulation
• Different showers, different prescription of matching/merging, different hadronization models, etc. -> **Herwig++**, **MadGraph**, **Pythia**, **Sherpa**

**Parton shower (PS):**
✓ Good approximation in soft/collinear regions
✗ Bad approximation in hard regions
**Herwig++**, **MC@NLO**, **Pythia**, **Sherpa**, **Vincia**,...

**Matrix element (ME):**
✗ Bad description in soft/collinear regions due to logarithmic enhancement
✓ Describes hard regions and regions of large angles very well

Combine ME + PS to obtain good description in soft/collinear and hard region
LO merging: Combination of several ME’s lead to double counting
• General prescription to avoid double counting: **CKKW, CKKW-L, MLM,**...
  [Catani, Krauss, Kuhn, Webber], [Loennblad], [Loennblad, Prestel], [Hamilton, Richardson, Tully]
  [Hoeche, Krauss, Schumann, Siegert],...
NLO matching:
- Combining NLO ME’s +PS
- Both contain NLO contributions
  (double counting between LO+PS and NLO real emission)
- NLO matching: General description to obtain NLO+PS result without double counting
  **MC@NLO, Powheg, +variants**

NLO merging:
- Merges multiple NLO ME’s + multiple LO ME’s to the PS
  **FxFx, MEPS@NLO, UNLOPS,...**
  [Frederix, Frixione][Lavesson, Loennblad]
  [Loennblad, Prestel][Platzer]
  [Gehrmann, Hoeche, Krauss, Schoenherr, Siegert]

**Note:** Differences in approaches and methods of merging, matching scale, introduce theoretical uncertainties
Electroweak corrections important for Run 2

NLO corrections mostly small for total cross section, but easily supersede QCD corrections in high $p_T$ tail
(mostly due to incomplete cancellation of large logarithms)
-> interesting region for new physics

Reduction strategies can be applied to EW calculations without modification

**BUT:**
- Computation much more involved due to increased number of diagrams (photon/W/Z)
- In general mixing between QCD and EW corrections
  Need to sum up ALL contributions at a given order
Simplest example: **Dijet production** [Dittmaier, Huss, Speckner]

- Need to sum up all possible contributions at a given order
- Conceptually clear, but subtle difficulties (different types of loop diagrams, subtraction terms proportional to interference term, etc.)
Conclusions

- Tremendous progress in NLO calculations within the last decade
- Calculation of NLO corrections highly automated
- So far mostly focused on QCD, but EW corrections field of highly active research
- Fixed order calculations mostly not sufficiently precise, inclusion of parton shower mandatory
- NLO + PS is the standard for LHC processes
- Next step: Automation of NNLO calculations....