MC Techniques for New Physics at NLO and Beyond

Pheno18 - University of Pittsburgh

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May 8, 2018

\textsuperscript{1}IPPP \rightarrow CP3, Louvain in Fall ’18
What this talk is about

This talk is *not*...

- Exhaustive. Unfortunately, lots of omissions.
- A technical lecture on next-to-next-to-...-leading order computations
- Definitely not about modest QCD corrections of $\sigma^{\text{NLO}}/\sigma^{\text{LO}} \sim 1 - 1.3$
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- A (qualitative) discussion on where perturbative QCD corrections and techniques are important new physics collider signatures
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This talk is...

- A summary of Monte Carlo (MC) advances from the past several years for studying new physics at colliders
- A (qualitative) discussion on where perturbative QCD corrections and techniques are important new physics collider signatures
- Propaganda highlighting Europe’s role in MC efforts
- Encouragement to hep-ex to continue telling the MC folks your needs
Importance of pQCD in Monte Carlo (MC) Tools

\[ h \rightarrow ZZ^* \rightarrow 4\ell \quad t\bar{t}\gamma \quad WW + 0j \]

- Higgs boson mass, electric charge of top quark, and triple gauge couplings are fundamental quantities in the Standard Model.
Importance of pQCD in Monte Carlo (MC) Tools

- Higgs boson mass, electric charge of top quark, and triple gauge couplings are fundamental quantities in the Standard Model
- Required MC and both Fixed Order (FO) / Resummed corrections
- Maturity of physics and technology enables application to BSM
  - Caveat: Utmost care required if $\Lambda_{\text{NewPhysics}} \gg \langle \Phi_{\text{SM}} \rangle$

$h \rightarrow ZZ^* \rightarrow 4\ell$  \hspace{1cm} \( t\bar{t}\gamma \) [1502.00586]  \hspace{1cm} WW + 0j [1507.03268]
Precision of Normalization ≠ Precision of Distribution

Not all observables $\hat{O}$ are well-defined (physically meaningful) when total cross section $\sigma$ is known only at Born/leading order (LO)

Famous ex: transverse momentum ($q_T$) of $W/Z$ system in $pp \rightarrow V + X$
- $q_T = 0$ at Born-level and singular at $O(\alpha_s)$
- Lowest order $q_T$ physical is when $\sigma$ is known at NLO w/ leading log. ($LL$) resummation (or $+PS$) $\implies d\sigma/dq_T$ is LO+LL accurate

Due to color structure, also true for heavy lepton pairs and dark $\gamma_D/Z'$
Anatomy of Automated Simulations at Next-to-Leading
The Monte Carlo Analysis Chain for Collider Experiments

Observation of some phenomenon

Idea or symmetry

\[ \mathcal{L} \]

NLOCT (QCD CT terms)

\( \text{UF O} \)

Integration

Parton Shower + Hadronization Model

Matrix Element Generator + Phase Space/Loop Integration

\( \text{FeynRules (UFO)} \)

\( \text{FeynArts} \)

Jet Clustering

Det. Sim.

Analysis

Experiment

 Lots of tools on the market, see hepforge.org/projects.
Basis of Scalar Loop Integrals (QCDLoop, Collier, etc)

In 2007, Ellis and Zanderighi released a basis of scalar integrals from which any 1-, 2-, 3-, or 4-point loop diagram could be built quickly. [0712.1851]

It was known by then that \((N > 4)\)-point loops could be reduced to combinations of \((N - 1)\)-point integrals.

- QCDLoop [0712.1851] returns coefficients of \(1/\epsilon^2\), \(1/\epsilon^1\), \(1/\epsilon^0\)
- Recent developments, e.g., Collier [1604.06792], focus on speed, complexity, and interfacing with event generators

No known basis for two-loop diagrams [See Anastasiou’s Talk]
- Progress from MSU (von Manteuffel), Louvain (Duhr), etc
Fast Scalar Loop Integrand Reduction

**Goal**: Decompose a **complicated** loop into sum of **simple**, **fast** loops

In 2006-7, OPP showed that the **integrand** of any 1-, 2-, 3-, or 4-point scalar loop integral could be evaluated numerically and efficiently.

For an \( m \)-point loop \( \mathcal{I} \) with propagators \( D_i \), one can write

\[
\mathcal{I} = \int d^d \bar{q} \ A(q), \quad \text{where}
\]

\[
A(q) = \frac{N(q)}{D_0 \overline{D}_1 \cdots \overline{D}_{m-1}},
\]

Implementations include: CutTools, Ninja, Collier, etc.

There remains a process-dependent, model-dependent but **finite** contribution (**rational term**) that can be derived from Feynman rules.
While the $R$ terms for the SM (EW+QCD) were known since 2009 [0903.0356; 0910.3130], automation for a generic model took more time.

**Solution:** NLOCT libraries for FeynRules [Degrande, 1406.3030]

\[ L_{\text{Renormalizable}} \rightarrow \text{FeynRules} \rightarrow \text{FeynArts} \rightarrow \text{R}^2 \text{FeynRules} \rightarrow \text{UFO} \]

Construct loops

Models files are systematically being written based on need/interest (happy to collaborate) [feynrules.irmp.ucl.ac.be/wiki/NLOModels]
Impetus for “loop revolution” came from another breakthrough: removing phase space **double counting** between matrix element and parton showers.

- A parton showers capture soft/collinear emissions off initial and final state legs. Unsuppressed since $\sigma \sim \alpha_s(k_T^2) \log(Q^2/k_T^2)$, $k^2_T \ll Q^2$.

**Solution:** MC@NLO [Frixione, Webber, hep-ph/0204244]. Essentially,

- If collinear/soft, it came from the **PS**. If wide-angle/hard, then **ME**.
- PS and ME describe these regions well, respectively.
With a little work, patience, and time, automated inclusive NLO and fully
differential NLO+PS results for BSM are now possible

- For low-mass $W'/Z'$, $\sigma^{\text{NLO}}/\sigma^{\text{LO}} \gg 1.2 - 1.3$, contrary to lore. Important for dark $\gamma_D/Z'_D$ searches. [B. Fuks and RR, 1701.05263]

- For $\tilde{t}\tilde{t} \rightarrow t\bar{t} + \text{MET}$, shape changes are large [Fuks, et al.,1412.5589]
GM model predicts new, exotic higgs $H^0$, $H^\pm$, $H^{\pm\pm}$ that couple to EW bosons

For total rate, QCD corrections to VBF known to be small, $\sigma^{NLO}/\sigma^{LO} \sim 1$ [Han, Valencia, Willenbrock, ('92)]

Not true differentially or with cuts

Basic jet kinematics shifts $+10 - +40\%$

Normalization $+10\%$

[More on GM at CW Chiang's talk]
During ’12-’15, series of papers on heavy $N$ at colliders had conflicting claims and $\sigma$ predictions.

**Problem (hindsight):** ill-defined collider signatures violated *pert. thry.*
During ’12-’15, series of papers on heavy $N$ at colliders had conflicting claims and $\sigma$ predictions.

**Problem (hindsight):** ill-defined collider signatures violated pert. thry.

**Solution:**
- Invert perturbativity requirements to enforce stability FO predictions
- **photon PDF** matching for VBF
- Missing $Z^*$ channel in GF

See Cai, Han, Li, **RR** [1711.02180]

Stable QCD corrections $\Rightarrow$ new signatures under perturbative control
The LHC is the only operational collider that can produce top quarks.

→ Natural testing ground for top-philic dark matter

Impact of **scale uncertainty** often **ignored** on setting limits on BSM rates

- **Take away**: In BSM searches, LO QCD theory uncertainty large, ignored, and weakens limits. (Let NLO be your friend!)

<table>
<thead>
<tr>
<th>((m_Y, m_X))</th>
<th>(\sigma_{LO} \text{ [pb]})</th>
<th>(\text{CL}_{LO} \text{ [%]})</th>
<th>(\sigma_{NLO} \text{ [pb]})</th>
<th>(\text{CL}_{NLO} \text{ [%]})</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (150, 25) GeV</td>
<td>0.658_{-24.0%}^{+34.9%}</td>
<td>98.7_{-13.0%}^{+0.8%}</td>
<td>0.773_{-10.1%}^{+6.1%}</td>
<td>95.0_{-0.4%}^{+2.7%}</td>
</tr>
<tr>
<td>II (40, 30) GeV</td>
<td>0.776_{-24.1%}^{+34.2%}</td>
<td>74.7_{-17.7%}^{+19.7%}</td>
<td>0.926_{-10.4%}^{+5.7%}</td>
<td>84.2_{-14.4%}^{+0.4%}</td>
</tr>
<tr>
<td>III (240, 100) GeV</td>
<td>0.187_{-24.4%}^{+37.1%}</td>
<td>91.6_{-18.1%}^{+6.4%}</td>
<td>0.216_{-11.4%}^{+6.7%}</td>
<td>86.5_{-5.5%}^{+8.6%}</td>
</tr>
</tbody>
</table>
NEW Monojet Uncertainties

Monojets are incredibly powerful! Great for \( pp \to Q\bar{Q} + j \) with \( Q \to \text{Dark Matter} + \text{jets} \) and \( (m_Q - m_{DM}) \ll m_Q \)

- Exhaustive look into QCD theory unc., which is large when summed

A Chakraborty, S Kuttimalai, HS Lim, MM Nojiri, RR

There is hope with friends!

[More Friday(?)]
1. Unstable logarithms of the form $\alpha_s(p_T^{\text{Veto}}) \log(p_T^{\text{Veto}}/M_B)$ appear. Resummable since still inclusive w.r.t. ultra-soft and -collinear rad.

2. Cancellations when summing over all radiations do not occur... [Eg., 1507.01652]. This is more serious...

\[ \hat{\sigma}(ab \to B) \]

\[ \sigma(pp \to B + X) \]

Hadronic process ($s$)

\[ f_a/p \]

Partonic process ($\hat{s}$)

\[ f_b/p \]

\[ \left( \frac{M_{WW}}{p_T^{\text{Veto}}} \right)^k \text{ and } \frac{\Lambda_{\text{QCD}}}{p_T^{\text{Veto}}} \log \left( \frac{M_{WW}}{p_T^{\text{Veto}}} \right). \]

Soln: Non-trivially, observe that residual terms have the form [1205.3806, 1412.8408, +others]:

If $p_T^{\text{Veto}}$ is in the “Goldilocks” region, such terms are numerically small:

\[ \Lambda_{\text{QCD}} \sim \mathcal{O}(1) \text{ GeV} \ll p_T^{\text{Veto}} \sim 20 - 40 \text{ GeV} \ll M_{WW} \]
Automated Jet Veto Resummation (2/2)

Jet veto physics very deep, but also rigorous and experimentally tested.

Computational framework quietly released in mg5amc@nlo [1412.8408]

- Jet veto resummation up to NLO+NNLL(Veto) in SCET
- BSM@NLO model file needed, but available from FeynRules
- Broadly improves color-singlet BSM searches [Fuks, RR, 1701.05263]
Outlook
NEW: Next-to-Leading Order in Electroweak Theory (1 slide)
A major new milestone has been reached in the past year:

- **Sherpa**: Automation of NLO QCD and EW corrections with Sherpa and Recola [1704.05783]
- **MadGraph5_aMC@NLO**: The automation of next-to-leading order electroweak calculations [1804.10017]

**NLO** = loop-induced at LO + real radiation (cures large Sudakov logs!)

<table>
<thead>
<tr>
<th>Process</th>
<th>Syntax</th>
<th>Cross section (in pb)</th>
<th>Correction (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( pp \to e^+e^- )</td>
<td>p p ( \to e^+e^- ) QCD=0 QCD=2 [QED]</td>
<td>5.2098 ( \pm 0.0005 ) ( \times 10^{3} )</td>
<td>( -0.73 \pm 0.01 )</td>
</tr>
<tr>
<td>( pp \to e^+e^- j )</td>
<td>p p ( \to e^+e^- j ) QCD=1 QCD=0 [QED]</td>
<td>9.4689 ( \pm 0.0012 ) ( \times 10^{3} )</td>
<td>( -1.11 \pm 0.02 )</td>
</tr>
<tr>
<td>( pp \to e^+e^- j j )</td>
<td>p p ( \to e^+e^- j j ) QCD=2 QCD=2 [QED]</td>
<td>3.1562 ( \pm 0.0003 ) ( \times 10^{3} )</td>
<td>( -1.83 \pm 0.02 )</td>
</tr>
<tr>
<td>( pp \to e^+e^- )</td>
<td>p p ( \to e^+e^- ) QCD=0 QCD=2 [QED]</td>
<td>7.5676 ( \pm 0.0083 ) ( \times 10^{3} )</td>
<td>( -0.49 \pm 0.02 )</td>
</tr>
<tr>
<td>( pp \to e^+e^- j j )</td>
<td>p p ( \to e^+e^- j j ) QCD=1 QCD=2 [QED]</td>
<td>1.5059 ( \pm 0.0001 ) ( \times 10^{4} )</td>
<td>( -1.00 \pm 0.02 )</td>
</tr>
<tr>
<td>( pp \to e^+e^- j j j j )</td>
<td>p p ( \to e^+e^- j j j j ) QCD=2 QCD=2 [QED]</td>
<td>5.1424 ( \pm 0.0004 ) ( \times 10^{3} )</td>
<td>( -1.97 \pm 0.02 )</td>
</tr>
<tr>
<td>( pp \to e^-\mu^+\mu^- )</td>
<td>p p ( \to e^-\mu^+\mu^- ) ( m_\mu=0 ) QCD=4 [QED]</td>
<td>1.2750 ( \pm 0.0000 ) ( \times 10^{-2} )</td>
<td>( -5.33 \pm 0.01 )</td>
</tr>
<tr>
<td>( pp \to e^+e^- \nu^+\nu^- )</td>
<td>p p ( \to e^+e^- \nu^+\nu^- ) ( m_\nu=0 ) QCD=4 [QED]</td>
<td>5.1444 ( \pm 0.0007 ) ( \times 10^{-1} )</td>
<td>( +3.67 \pm 0.02 )</td>
</tr>
<tr>
<td>( pp \to H^+H^- )</td>
<td>p p ( \to H^+H^- ) QCD=3 [QED]</td>
<td>6.7643 ( \pm 0.0001 ) ( \times 10^{-2} )</td>
<td>( -4.03 \pm 0.02 )</td>
</tr>
<tr>
<td>( pp \to H^+H^- j )</td>
<td>p p ( \to H^+H^- j ) QCD=3 QCD=3 [QED]</td>
<td>1.4551 ( \pm 0.0001 ) ( \times 10^{-2} )</td>
<td>( -5.87 \pm 0.02 )</td>
</tr>
<tr>
<td>( pp \to W^+W^- )</td>
<td>p p ( \to W^+W^- ) QCD=0 QCD=3 [QED]</td>
<td>2.9268 ( \pm 0.0002 ) ( \times 10^{-1} )</td>
<td>( -4.22 \pm 0.01 )</td>
</tr>
<tr>
<td>( pp \to ZZ+\gamma )</td>
<td>p p ( \to Z+\gamma ) QCD=0 QCD=3 [QED]</td>
<td>8.2874 ( \pm 0.0004 ) ( \times 10^{-2} )</td>
<td>( -6.21 \pm 0.02 )</td>
</tr>
<tr>
<td>( pp \to ZZ )</td>
<td>p p ( \to ZZ ) QCD=0 QCD=3 [QED]</td>
<td>1.6764 ( \pm 0.0001 ) ( \times 10^{-2} )</td>
<td>( -9.47 \pm 0.02 )</td>
</tr>
<tr>
<td>( pp \to H+H+ )</td>
<td>p p ( \to H+H+ ) QCD=3 QCD=3 [QED]</td>
<td>2.1005 ( \pm 0.0003 ) ( \times 10^{-3} )</td>
<td>( -8.81 \pm 0.02 )</td>
</tr>
<tr>
<td>( pp \to H+H+ j )</td>
<td>p p ( \to H+H+ j ) QCD=3 QCD=3 [QED]</td>
<td>2.4408 ( \pm 0.0000 ) ( \times 10^{-3} )</td>
<td>( +1.64 \pm 0.02 )</td>
</tr>
<tr>
<td>( pp \to H+H+ j j )</td>
<td>p p ( \to H+H+ j j ) QCD=3 QCD=3 [QED]</td>
<td>2.7827 ( \pm 0.0001 ) ( \times 10^{-4} )</td>
<td>( -12.52 \pm 0.10 )</td>
</tr>
<tr>
<td>( pp \to H+H+ j j j j )</td>
<td>p p ( \to H+H+ j j j j ) QCD=3 QCD=3 [QED]</td>
<td>2.6914 ( \pm 0.0003 ) ( \times 10^{-4} )</td>
<td>( -11.10 \pm 0.02 )</td>
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<tr>
<td>( pp \to H+H+ j j j j j j )</td>
<td>p p ( \to H+H+ j j j j j j ) QCD=3 [QED]</td>
<td>2.4119 ( \pm 0.0003 ) ( \times 10^{-4} )</td>
<td>( -4.54 \pm 0.02 )</td>
</tr>
<tr>
<td>( pp \to H+H+ j j j j j j j j )</td>
<td>p p ( \to H+H+ j j j j j j j j ) QCD=3 [QED]</td>
<td>5.0456 ( \pm 0.0006 ) ( \times 10^{-5} )</td>
<td>( -0.84 \pm 0.02 )</td>
</tr>
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</table>

Table 2: Processes considered in sect. 6.2. The second column reports the MG5_aMC syntax used to generate them. The third and fourth columns display the fully-inclusive results for the quantities defined in eq. (6.12). The fifth column shows the results for the fractional correction defined in eq. (6.14). All uncertainties are due to MC integration errors.
Automated Monte Carlo at NNLO (1 slide)
NNLO Monte Carlos for BSM

When achieved, will MC@NNLO be important for BSM?
- Not for discovery, except when “NNLO” really means “NLO”
- **Remember**: “NLO Monte Carlos” is a *technology paradigm*

\[ \sigma = \frac{1}{N} + \frac{2}{N} + \frac{3}{N} \]

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For loop-induced processes, MC@NLO $\Rightarrow$ 1-loop @ LO

- $gg \rightarrow S^0, A^0$: QCD corrections are **large** ($\sigma/\sigma^{LO} \sim 2 - 3$)
- Heavy $N$ production at $\sqrt{s} > 25$ TeV dominated by GF

[RR, Spannowsky, Waite, 1706.02298]
One more thing
SURPRISE
Summary

Over the past decade, an evolution in QCD and Monte Carlo technology!

- New tools + new formalisms $\implies$ new sensitivity at $pp$ colliders
- Automation of SM and BSM@NLO in QCD and EW
- Automation of some types of resummation ($+\text{PS}$, Veto, pipeline)

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Maturity of $N^\text{LO}/N^k\text{LL}$ formalism allows application to BSM

- Reassess/rewrite collider signatures that are robust over large mass hierarchies and colliders, i.e., works at $\sqrt{s} = 14, 27, \text{ and } 100$ TeV
- For first time, first QCD emission is under control at all $p_T$ scales $\implies$ jet observables as bkg discriminant now possible
- For first time, QCD and EW loop-induced processes now automated

Last words:

“The LHC is planned to run over the next 20 years, with several stops scheduled for upgrades and maintenance work.” [press.cern]

High-Luminosity LHC and Belle II goals: 3-5 ab$^{-1}$ and 50 ab$^{-1}$

Premature to claim “nightmare scenario” (SM Higgs + nothing else)

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Thank you.