Standard Model Theory

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Max Planck Institute for Physics

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Plan

I will highlight here a few broad directions with substantial recent progress but still in need for improvements (NB: this is a personal selection, not an exhaustive list)

The keyword: precision

Why do we care about precise theoretical predictions?
Precision theory

• LHC already collected around 150 fb\(^{-1}\) at 13 TeV. No major energy increase foreseen in the next 20 years
• Up to now, collected only 5% of the full expected dataset (3 ab\(^{-1}\))
• The reach of many precision tests will increase considerably
• Processes with a tiny cross section will benefit incredibly from the increase in luminosity + expect improvements in search techniques that are background limited
• Possible discoveries at the LHC might be indirect ones
  ⇒ precision as tool for indirect discoveries
Given the detailed projections from the experiments substantial further progress will be needed from theory calculations if these are not to become a limiting factor in interpreting a wide range of High-Luminosity LHC (HL-LHC) data
One example (out of many)

Higgs couplings after HL-LHC

Largest contribution to the uncertainty from theory

⇒ see talk by H. Abramowicz
Precision through perturbation

colliding protons

scattering between elementary partons

Parton distribution functions (PDFs): extracted from data at one scale, evolution is perturbative

Perturbative cross section: Expansion in the coupling constant (LO, NLO, NNLO ... )

\[
\frac{d\sigma_{pp\rightarrow\text{hadrons}}}{dX} = \sum_{a,b} \int dx_1 dx_2 f_a(x_1, \mu_F) f_b(x_2, \mu_F) \times \frac{d\hat{\sigma}_{ab\rightarrow\text{partons}}(\alpha_s(\mu_R), \mu_R, \mu_F)}{dX} + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^n}{Q^n}\right)
\]
Perturbation in a nutshell

**Leading order (LO):**

adapted from M. Wiesemann
Perturbation in a nutshell

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**Leading order (LO):**

![Orange](image1.png)

**Next-to-Leading order (NLO):**

![Orange with Face](image2.png)

**NNLO:**

![Orange with Shocked Face](image3.png)

adapted from M. Wiesemann
Perturbation in a nutshell

Leading order (LO):

Next-to-Leading order (NLO):

NNLO:

All-orders?

adapted from M. Wiesemann
Perturbation in a nutshell

**Leading order (LO):**

**Next-to-Leading order (NLO):**

**NNLO:**

**Experimental data:**

adapted from M. Wiesemann
Perturbation in a nutshell

**Take-home messages:**

1. Assessing how reliable a perturbative approximation is a very hard task. The assignment of a robust theoretical uncertainty is crucial to claim deviations
   Conventionally: renormalization/factorization scale variation around the “physical scale”, look at convergence, see later

2. While perturbation theory relies on theoretical ground, decades of experience in data/theory comparison is incredibly valuable
Known at $N^3$LO

1. Inclusive Higgs production in the large-$m_t$ approximation

$$\sigma = 48.58\text{pb}^{+2.22\text{pb}(4.56\%)}_{-3.27\text{pb}(-6.72\%)} \text{theory} \pm 1.56\text{pb}(3.2\%)(\text{PDF + } \alpha_s)$$

- Anastasiou et al. 1602.00695
- Mistlberger 1802.00833

2. Inclusive Vector Boson Fusion Higgs cross-section (DIS approx.)

- Dreyer & Karlberg 1606.00840

NB: NNLO non-factorizable effects sub-percent

- Liu et al. 1906.10899
New at N$^3$LO

**New at N$^3$LO:**
Higgs rapidity (using a threshold expansion)

⇒ Remarkable stability of perturbative expansion

Dulat, Mistlberger, Pelloni 1810.09462
N^{3}\text{LO}: future prospects?

In the two cases where N^{3}\text{LO} results are known, the series shows a remarkable convergence and stability:

• it will be interesting to see whether the same pattern holds for Drell-Yan production and other processes
• it will be interesting to see how stable the picture is with realistic LHC fiducial cuts

⇒ see talk by C. Duhr
Core processes at $N^3LO$

Experimental precision of core $2 \rightarrow 1$ and $2 \rightarrow 2$ processes likely to approach 1% precision over a substantial range of phase-space.

$N^3LO$ predictions do not normally reach 1% precision $\Rightarrow$ strong case for seeking $N^3LO$ accuracy, also in the PDF extraction.

Example:

$\sigma_Z / \sigma_{ZZ} = O(100) \quad \mathcal{L}_{HL} / \mathcal{L}_{\text{RunI}} = O(100)$

$\Rightarrow$ permille statistical error in $ZZ$ at HL-LHC.
status of NNLO

Things are developing rapidly, but a number of conceptual and technical challenges remain to be faced ⇒ see talk by C. Duhr
Status of NNLO

Every SM $2\rightarrow2$ process known at NNLO

No full $2\rightarrow3$ process known at NNLO

Things are developing rapidly, but a number of conceptual and technical challenges remain to be faced ⇒ see talk by C. Duhr
NNLO for 2→3

A number of crucial processes involving a 2→3 structure beyond today’s state-of-the-art for NNLO calculations (e.g. 3-jet, ttH, ttV, H+2jets, …)

Example:

$t\bar{t}H$ expected to have 2% statistical precision at the end of the HL-LHC. Without NNLO QCD and NLO electroweak (EW) calculations such an experimental precision cannot be fully exploited.
Five-particle 2-loop amplitudes

- **All QCD amplitudes in the planar limit are known analytically** [Abreu, Dormans, Febres Cordero, Ita, Page ’18] Previous numerical [Badger, Brønnum-Hansen, Hartanto, Peraro ’17][Abreu, Cordero, Ita, Page, Zeng ’17] [Abreu, Cordero, Ita, Page, Sotnikov ’18][Badger, Brønnum-Hansen, Gehrmann, Hartanto, Henn, Lo Presti, Peraro ’18] and analytical results [Gehrmann, Henn, Lo Presti ’15][Dunbar, Perkins ’16] [Badger, Brønnum-Hansen, Hartanto, Peraro ’18] in the planar approximation

- **Full-color $\mathcal{N} = 4$ super-Yang-Mills and $\mathcal{N} = 8$ supergravity amplitudes** (at symbol level) [D.C., Gehrmann, Henn, Wasser, Zhang, Zoia ’18 ’19][Abreu, Dixon, Herrmann, Page, Zeng ’18 ’19]

- **Full-color five-gluon all-plus helicity amplitude** [Badger, D.C., Gehrmann, Heinrich, Henn, Peraro, Wasser, Zhang, Zoia ’19]

  $\implies$ Very first complete analytic two-loop five-particle amplitude!

$\Rightarrow$ see talk by D. Chicherin
Does NLO scale uncertainty account for the size of NNLO?

For many processes NNLO scale band is $\pm 2\%$

But only in 3/17 cases is NNLO (central) within NLO scale band...
NNLO for diboson production

Clear NLO not enough to describe current LHC data
Same conclusion in all measurements examined so far
Top@NNLO: spin correlation

ATLAS reported a 3.2σ deviation in the azimuthal angle between between leptons in fully leptonic top-decay mode

NNLO calculation including spin correlation

Fiducial level: good agreement NNLO & data

Inclusive level: less good agreement, mostly likely due to generators used in extrapolation

[EW effects tiny, see Frederix et al. 1804.10071]

Reminiscent of discrepancy in inclusive WW cross-section reported a few years ago
**H+jet@NLO with top mass**

**HEFT:** $m_t \to \infty$ limit

NLO loop-induced: different scaling behaviour at large $p_T$

- large $p_T$ sensitive to BSM
- settles a longstanding question about uncertainties due to unknown top-mass effects
$H(\rightarrow 4l) + \text{jet} @ \text{NNLO}$

Good agreement with ATLAS and CMS data (within their larger errors)

**ATLAS lepton isolation:** removal of non-isolated jet

**CMS lepton isolation:** removal of non-isolated lepton → worse convergence of acceptance at fixed-order
\( \text{H}(\rightarrow 4l) + \text{jet} @ \text{NNLO} \)

Chen, Gehrmann, Glover, Huss 1905.13738

Good agreement with ATLAS and CMS data (within their larger errors)

Example illustrates that theoretical calculations are up to the task of providing useful input (e.g. choice of isolation requirements, cuts, etc.)

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Example illustrates that theoretical calculations are up to the task of providing useful input (e.g. choice of isolation requirements, cuts, etc.)

But example also illustrates shortcomings of NNLO calculations, where only 4 leptons from the Higgs decay are present

**ATLAS**

CMS **lepton isolation**: removal of non-isolated **lepton** → worse convergence of acceptance at fixed-order
NNLO or PS?

**NNLO:**
good perturbative accuracy, accurate inclusive cross-sections, but limited to low multiplicity and parton level only

**Parton shower (PS):**
less accurate, but realistic description, including multi-parton interactions, resummation, hadronization effects
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Matching of NLO & PS achieved in seminal papers about 15 years ago

Today: NLOPS codes (MC@NLO, POWHEG, Sherpa) well-established and used in all advanced LHC analyses
NNLOPS

Matching of NNLO and PS (NNLOPS) is a must to have the best perturbative accuracy with a realistic description of final state.

**NNLOPS**: currently three methods exist (UNNLOPS, Geneva, MiNLO) but very hard to extend to generic $2 \to 2$ processes. *New approaches/ideas required?*

Hoeche, Li, Prestel [UNNLOPS]
Astill, Bizon, Hamilton, Karlberg, Nason, Re, GZ [MiNLO]
Alioli, Bauer, Berggren, Guns, Tackmann, Walsh [Geneva]
NNLOPS

Example: associated HW production with cuts used by HXSWG

- PS and hadronization cause migration between jet-bins
- Difficult to reach high accuracy in jet-binned observables

Bizon et al. 1603.01620
NNLOPS for WW

Re, Wiesemann, GZ 1805.09857

→ NNLOPS physical down to $p_T = 0$

→ NNLOPS cures perturbative instabilities ($p_T^{\text{miss}}$ cut)

→ NNLOPS induces additional shape effects
EW effects & accuracy at high $p_T$

Understanding logarithmically enhanced EW effects at high $p_T$, also in relevant background processes, will be crucial to fully exploit future data.

Examples:
Two most important examples are high-$p_T$ Higgs production and dark matter searches.

Biedermann et al. 1611.05338
Public codes

Selected pheno studies

Amongst many others OpenLoops has successfully been applied in the following precision studies for the LHC and ILC. They include parton-level NLO (QCD and EW) and NNLO calculations as well as simulations based on NLO+PS matching (S-MC@NLO) and multi-jet merging at NLO (MEPS@NLO) or for loop-induced processes (MLM@Loop^2).

<table>
<thead>
<tr>
<th>Process</th>
<th>Method</th>
<th>Monte Carlo</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>e^+e^- → W^+W^-b\bar{b}(H)</td>
<td>NLO</td>
<td>WHIZARD</td>
<td>arXiv:1609.03390</td>
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<td>pp → W^+W^-b\bar{b}</td>
<td>NLO+PS</td>
<td>POWHEG-BOX</td>
<td>arXiv:1607.04538</td>
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<tr>
<td>pp → HH</td>
<td>NNLO</td>
<td>MUNICH</td>
<td>arXiv:1606.09519</td>
</tr>
<tr>
<td>pp → two-leptons+1,2 jets</td>
<td>NLO EW</td>
<td>Sherpa &amp; MUNICH</td>
<td>arXiv:1511.08692</td>
</tr>
<tr>
<td>pp → W^++1,2,3 jets</td>
<td>NLO EW</td>
<td>Sherpa &amp; MUNICH</td>
<td>arXiv:1412.5157</td>
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<td>MUNICH</td>
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<td>MUNICH</td>
<td>arXiv:1405.2219</td>
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<td>pp → WWW+0,1 jet</td>
<td>MEPS@NLO</td>
<td>Sherpa</td>
<td>arXiv:1403.7516</td>
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<tr>
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<td>MEPS@NLO</td>
<td>Sherpa</td>
<td>arXiv:1402.6293</td>
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<td>q\bar{q} → t\bar{t}</td>
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<td>private</td>
<td>arXiv:1404.6493</td>
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<td>Herwig++</td>
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<td>arXiv:1309.5912</td>
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<tr>
<td>pp → four-leptons+0,1 jet</td>
<td>MEPS@NLO</td>
<td>Sherpa</td>
<td>arXiv:1309.0500</td>
</tr>
</tbody>
</table>
Public codes

**MATRIX**

(MUNICH Automates qT-subtraction and Resummation to Integrate X-sections)

Massimiliano Grazzini, Stefan Kallweit and Marius Wiesemann (e-Print: arXiv:1711.06631)

pp → Z
pp → W
pp → H
pp → W⁺, W⁻, Z
pp → W⁺W⁻, ZZ
pp → W⁺W⁻, ZZ
pp → WW, ZW
pp → four-lepton

S. Kallweit, M. Grazzini, D. Rathiev, A. Torre; Phys.Lett. B731 (2014) 204-207 (e-Print: 1309.7000),

F. Cascioli, T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel,

T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel,
S. Kallweit, M. Grazzini, S. Pozzorini, D. Rathiev, M. Wiesemann; JHEP 1608 (2016) 140
(e-Print: arXiv:1605.02716)

Public codes

EERAD3

The program EERAD3 computes the QCD contributions to event shapes and jet rates in electron-positron annihilation at parton level to order $\alpha_s^3$. For three-jet production and related observables, this corresponds to NNLO corrections.

The user can define cuts and choose the observables to be computed via an input card. The output is given in the form of histogram data.

Download

Version 1.0 of the program can be downloaded as eerad3-1.0.tar.gz.

The input files as well as examples can also be downloaded separately:
- eerad3.input
- eerad3_combine/input
- eerad3_dist.input
- examples and reference results

Installation and usage are described in arXiv:1402.4140.

Documentation and Literature


Results for event shapes, jet rates and moments produced with the program can be found e.g. in

The current members of the EERAD3 project are

- Aude Gehmann-De Ridder <gehra@phys.ethz.ch>
- Thomas Gehrmann <thomas.gehrmann@uzh.ch>
- Nigel Glover <e.w.n.glover@durham.ac.uk>
- Gudrun Heinrich <gudrun@mpp.mpg.de>
Public codes

MCFM - Monte Carlo for FeMtoHorn processes

Authors: John Campbell, Keith Ellis, Walter Giele, Tobias Neumann, Ciaran Williams.

Overview

This is the homepage for the parton-level Monte Carlo program MCFM. The program is designed to calculate cross-sections for various femtobarn-level processes at hadron-hadron colliders. For most processes, matrix elements are included at next-to-leading order and incorporate full spin correlations. Some processes are also available at next-to-next-to-leading order in QCD and/or can account for next-to-leading order weak effects. For more details, including a list of available processes, view the documentation (PDF).


The current members of the EERAD3 project are

- Aude Gehmann-De Ridder <gehra@phys.ethz.ch>
- Thomas Gehmann <thomas.gehrmann@uzh.ch>
- Nigel Glover <n.glover@durham.ac.uk>
- Gudrun Heinrich <gudrun@mpp.mpg.de>
The POWHEG BOX Project

The POWHEG BOX is a general computer framework for implementing NLO calculations in shower Monte Carlo programs according to the POWHEG method. It is also a library, where previously included processes are made available to the users. It can be interfaced with all modern shower Monte Carlo programs that support the Les Houches Interface for User Generated Processes.

Available Processes

- POWHEG-BOX/W
- POWHEG-BOX/Z

Selected phe

Amongst many other studies for the LHC e+e- calculations as well a merging at NLO (ME)
Public codes

Welcome to the MadGraph5_aMC@NLO Wiki

This wiki is dedicated to the MadGraph5_aMC@NLO project.

MadGraph5_aMC@NLO is a framework that aims at providing all the elements necessary for and BSM phenomenology, such as the computations of cross sections, the generation of hard events and their matching with event generators, and the use of a variety of tools relevant for event manipulation and analysis. Processes can be simulated to LO accuracy for any user-defined Lagrangian, and the NLO accuracy in the case of QCD corrections to SM processes. Matrix elements at the tree- and one-loop-level can also be obtained.

MadGraph5_aMC@NLO is the new version of both MadGraph5 and aMC@NLO that unifies the and NLO lines of development of automated tools within the MadGraph family. It therefore supersedes all the MadGraph5 1.5.x versions and all the beta versions of aMC@NLO.

The standard reference for the use of the code is:


A fuller list of papers, tailored to specific needs, will be given later.

Download:

The latest stable release can downloaded as a tar.gz package at http://launchpad.net/madgraph5, or through the Bazaar versioning system, using bazaar branches lp:madgraph5

Available variants

- POWHEG-BOX/W
- POWHEG-BOX/Z
- Aude
- Thoma
- Nigel
- Gudrun Heinrich <gudrun@mpg.de>
Public codes

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The latest stable release can downloaded as a tar.gz package at http://madgraph.mpp.mpg.de/madgraph5, or through the.CodeAnalysis system using bash and

+ many more codes with (semi) automated implementation of NLO, NNLO, NLO-EW, NLO-BSM
Top mass

Top-mass determination is a very challenging theoretical problem

No consensus in the theory community on a number of points

- Optimal observables?
- Effect of cutoff in Monte Carlo?
- Linear power corrections?
- Which mass is better when?
- Impact of width?
- What type of infrared sensitivity?

Progress in understanding differences and reaching consensus

HE-LHC Working Group report 1902.04070

Analytic progress in understanding power corrections: Ravasio, Nason, Oleari 1810.10931
Top mass

In summary, from a theoretical point of view, much work is still needed to put the top mass measurements at the HL-LHC on a solid ground. Such work should comprise more thorough experimental work aimed at understanding and reduce the sources of errors; theoretical work in the framework of Monte Carlo studies and simulation; and formal theoretical work aimed at understanding conceptual aspects. Such work is already under way, and it is expected that much more will be understood by the time the High Luminosity program starts. Thus, in spite of the many challenges, one can expect that a theoretical precision matching the foreseeable experimental errors for top mass measurements at the HL-HLC can be achieved.

Progress in understanding differences and reaching consensus

HE-LHC Working Group report 1902.04070
Top mass

Realistic top-quark simulation: considerable theoretical progress in matching NLO & PS in a “resonance-aware” way

Two main conclusions:

• Best observable remains the reconstructed top invariant mass (not lepton observables or $E_{b,\text{max}}$)

• Residual theoretical uncertainty of O(200 MeV) if no smearing to account for experimental uncertainties is performed and small R is used (R=0.4-0.5)

<table>
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<tr>
<th>Obs</th>
<th>gen</th>
<th>shower</th>
<th>$R = 0.4$</th>
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<td>$m_{Wb_j}^{\text{max}}$ [GeV]</td>
<td>$b\bar{b}4\ell$</td>
<td>Py8.2</td>
<td>172.509 ± 0.002</td>
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<tr>
<td></td>
<td></td>
<td>Py6.4</td>
<td>172.487 ± 0.003</td>
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<td>Hw7.1</td>
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</tbody>
</table>

$E_{b,\text{max}} \rightarrow$ Agashe et al. 1903.03445

Leptonic obs. $\rightarrow$ Frixione, Mitov 1407.2763

Ravasio et al. 1906.09166
Resummations

Current status: in several cases, the accuracy of all-order resummed predictions pushed to NNLL or even N^3LL, properly matched to fixed order
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• On one side, once an accurate fixed order result is available, the impact of the resummation is limited to regions of low transverse momenta, see e.g. Melnikov LHCP 2019

3) NNLO QCD computations work in “hard kinematic regions”. For an object with the invariant mass $O(100) \text{ GeV}$, “hard” means down to transverse momenta $O(30) \text{ GeV}$. This requires NNLO. Resummations are important but with NNLO results available, they become relevant at low(er) transverse momenta;
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Both points seem to imply that resummations are not quite that useful. I want to argue that this is not true.
Resummations

Selected example: transverse momentum spectrum of weak bosons at N^3LL+NNLO with fiducial cuts

Bizon et al. 1905.05171
Joint resummations

Even if the hard scale is of $O(100 \text{ GeV})$, fiducial cuts can push all the kinematics at low transverse momentum values, e.g. for Higgs production the bulk of the cross section lies well below 30 GeV.

**Double differential resummed predictions**, e.g. NNLL resummed predictions for the Higgs transverse momentum with a veto on jets.

Reminder: jet-veto is required in the WW decay channel to suppress top background.

Monni et al. ’19
Other joint resummations

Increasing interest in resummations in more exclusive regions

- $p_{T,H}$ and small-$x$
  - Lustermans et al. 1605.027400; Muselli et al. 1701.01464

- $p_{T,H}$ and large-$x$
  - Marzani 1511.06039; Forte and Muselli 1511.05561

- small-$x$ and large-$x$
  - Bonvini and Marzani 1802.07758

- $p_{T,H}$ and jet-radius
  - Banfi et al. 1511.02886

- $p_{T,V}$ and 0-jettiness
  - Lustermans et al. 1901.03331

- 2 angularities
  - Larkoski et al. 1501.4458; Procura et al. 1806.10622

Resummations no longer limited to inclusive observables

⇒ closer connection between resummed predictions and measurements
Conclusions

• Precision QCD crucial to enhance sensitivity in the search for physics beyond the SM

• Theoretical calculations are reaching an impressive level of sophistication

• I presented a selection of recent new theoretical results
  ➔ $N^3LO$, $NNLO$, automated EW, NLO+EW, loop-induced, NNLOPS, (joint) resummations, heavy-flavour effects, …

• Lots of room and need for improvements in various areas

• Precision is not just about computing one more order in perturbation theory, it is really a multilateral challenge