Theory summary
SM: Loops and Multilegs Working Group

Ansgar Denner
University of Würzburg

for the convenors
Simon Badger, Ansgar Denner, Joey Huston

Physics at TeV Colliders, Les Houches

10.6.2015

Overview

Loops and Multilegs theory projects at Les Houches 2015

- comparison of NLO EW automated calculations
- high-precision wishlist
- propagation of NNLO results

More experimentally oriented projects

see experimental summary by Joey Huston

Many additional benefits of Les Houches 2015

- numerous fruitful bilateral discussions
  between theorists and experimentalists
  between theorists and theorists
  $\Rightarrow$ triggers for future work

Outline

Automation of NLO corrections

- NLO QCD corrections: full automation established
  various codes: GOSAM, HELAC-NLO, MADGRAPH5_AMC@NLO, OPENLOOPS, ...
- NLO EW corrections: automated tools being developed
  full automation available soon

automated tools for electroweak corrections

tool	collaboration	publ. applications
GOSAM	Cullen et al.	
HELAC-NLO?	Bevilacqua et al.	
MADGRAPH5_AMC@NLO	Frixione et al.	$pp \to t\bar{t} + \{H, Z, W\}$
OPENLOOPS	Cascioli et al.	$pp \to W+ \leq 3j$
RECOLA	Actis et al.	$pp \to jjl^+l^-$

Technical comparisons of EW corrections

- only few calculations with automated tools available
- codes do not yet work out of the box

$\Rightarrow$ perform comparisons with three existing calculations from different groups

plan for comparisons (coordination A. Denner)

process	publication	collaboration
$pp \to l^+l^-jj$	arXiv:1411.0916	RECOLA
$pp \to l\nu_l jj$	arXiv:1412.5157	OPENLOOPS
$pp \to t\bar{t}H$	arXiv:1504.03446	MADGRAPH5_AMC@NLO

parameters and setup as in publications (see also wiki)

at least one group volunteered to compare to each calculation

arXiv:1412.5157: contains $pp \to Wjj$ for on-shell W bosons
OPENLOOPS will provide off-shell calculation

Sudakov approximation

Enhancement of EW corrections by Sudakov logarithms

- EW corrections involve Sudakov logarithms
  $\propto (\alpha/\sin\theta_{\mathrm{w}}^2)\ln^2(E^2/M_{\mathrm{W}}^2)$
- $\Rightarrow$ EW corrections of $\mathcal{O}(10\% - 40\%)$ in TeV range
  (tails of distributions/highly boosted events)
  $\Rightarrow$ EW NNLO effects relevant
- corrections from leading double logarithms negative
- extensive literature on EW Sudakov corrections
  at NLO, NNLO, resummation via evolution equations
  M. Ciafaloni, P. Ciafaloni, Comelli; Beccaria, Renard, Verzegnassi; Beenakker, Werthenbach;
  Denner, Pozzorini; Melles; Fadin, Lipatov, Martin; Hori, Kawamura, Kodaira;
  Jantzen, Kühn, Penin, Smirnov; Chiu, Fuhrer, Golf, Kelley, Manohar, ...
- most papers focus on virtual corrections
- real W/Z emission via (tree-level) multipurpose MC codes

Sudakov approximation for EW NLO corrections

approximation of NLO EW corrections by Sudakov logarithms

- much simpler than full NLO EW
- complete set of formulas for virtual NLO Sudakov logarithms for arbitrary processes (not mass-suppressed) available Denner, Pozzorini '01
- valid only in Sudakov regime:
  all invariants must be large $s, |t|, \ldots \gg M_W^2$
- constant corrections of $\mathcal{O}(\alpha)$ not included
  $\Rightarrow$ accuracy at best few per cent
- effects of photon radiation must be added independently
- other sources of enhancement can give large effects

$\Rightarrow$ assess quality of approximation by comparison to full calculations

Comparison of full NLO with Sudakov approximation

Available tools for Sudakov approximation

- SHERPA (contact: Jennifer Thomson)
- Mauro Chiesa, Fulvio Piccinini et al. for $\mathrm{W/Z} + \mathrm{jets}$ (implemented in ALPGEN)

plan: compare Sudakov approximation to exact EW NLO corrections for distributions

planned comparisons

process	publication	collaboration
$\mathrm{pp} \to \mathrm{l^+ l^- jj}$	arXiv:1411.0916	RECOLA
$\mathrm{pp} \to \mathrm{l}\nu_\mathrm{l}\mathrm{jj}$	arXiv:1412.5157	OPENLOOPS

parameters and setup as in publications (see also wiki)

distributions in publications and possibly additional ones

Study of cross-section ratio for Z/γ^*+jets and γ+jets

project in collaboration with Tools and Monte-Carlos WG
proposal and coordination: Vitaliano Ciulli (CMS)

plan: comparison to CMS results of arXiv.1505.06250 for $\sigma(pp \to Z/\gamma^* + jets)/\sigma(pp \to \gamma + jets)$

- in Sudakov approximation
- with exact NLO EW corrections
- including QCD/QED shower corrections
- Rivet analysis being prepared (V. Ciulli)

Contributers

- SHERPA (contact: Jennifer Thomson)
- Mauro Chiesa, Fulvio Piccinini et al.
- OPENLOOPS (contact: Jonas Lindert)

Outline

Evolution of wishlist

History of wishlist

- Les Houches 2005: construction of NLO QCD wishlist
- amended at Les Houches 2007 and 2009
- Les Houches 2011: progress in NLO automation
  $\Rightarrow$ no need for NLO wishlist
  instead: NNLO wishlist with few processes of high priority
- Les Houches 2013: ambitious high-precision wishlist
  including NNLO (N^{3}LO) QCD, NLO EW, resummation

Les Houches 2015

- NLO EW automation upcoming
- large progress in NNLO QCD calculation
  (example: N-jettiness subtraction $\Rightarrow$ talk by Petriello)

LH13 wishlist : Higgs and related

Process	State of the Art	Desired
H	$d\sigma$ @ NNLO QCD (expansion in $1/m_t$) full m_t/m_b dependence @ NLO QCD and @ NLO EW NNLO+PS, in the $m_t \to \infty$ limit	$d\sigma$ @ NNNLO QCD (infinite-m_t limit) full m_t/m_b dependence @ NNLO QCD and @ NNLO QCD+EW NNLO+PS with finite top quark mass effects
H + j	$d\sigma$ @ NNLO QCD (g only) and finite-quark-mass effects @ LO QCD and LO EW	$d\sigma$ @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(VBF) @ NLO EW $d\sigma$(gg) @ NLO QCD (infinite-m_t limit) and finite-quark-mass effects @ LO QCD	$d\sigma$(VBF) @ NNLO QCD + NLO EW $d\sigma$(gg) @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW σ_{tot}(gg) @ NLO QCD (infinite-m_t limit)	with $H \to b\bar{b}$ @ same accuracy $d\sigma$(gg) @ NLO QCD with full m_t/m_b dependence
tH and $\bar{t}$H	$d\sigma$(stable top) @ LO QCD	$d\sigma$(top decays) @ NLO QCD and NLO EW
t$\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD and NLO EW
gg $\to$ HH	$d\sigma$ @ NLO QCD (leading m_t dependence) $d\sigma$ @ NNLO QCD (infinite-m_t limit)	$d\sigma$ @ NLO QCD with full m_t/m_b dependence

LH13 wishlist : Higgs and related

Anastasiou, Duhr, Dulat, Herzog, Mistlberger 1503.06056

Hamilton, Nason, Re, Zanderighi 1309.0017
Hamilton, Nason, Zanderighi 1501.04637

Boughezhal, Focke, Giele, Liu, Petriello 1505.03893

Boughezhal, Caola, Melnikov, Petriello, Schulze 1504.07922

gg only : Chen, Glover, Gehrmann, Jaquier 1408.5325

automated NLO
e.g. aMC@NLO_MG5

		Desired
		dσ @ NNNLO QCD (infinite-m_t limit)
		full m_t/m_b dependence @ NNLO QCD and @ NNLO QCD+EW
	NNLO+PS, in the $m_t \to \infty$ limit	NNLO+PS with finite top quark mass effects
		dσ @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW
		dσ(VBF) @ NNLO QCD + NLO EW
		dσ(gg) @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW
		with $H \to b\bar{b}$ @ same accuracy
		dσ(gg) @ NLO QCD with full m_t/m_b dependence
		dσ(top decays) @ NLO QCD and NLO EW
		dσ(top decays) @ NLO QCD and NLO EW
		dσ @ NLO QCD with full m_t/m_b dependence

finite top mass corrections at NNLO still challenging

Les Houches 2015 wishlist

$\Rightarrow$ revision of wishlist required

Wishlist is useful!

- provides snapshot of state-of-the-art
- prioritizes required theoretical calculations
- supports funding applications

Aims

- update the 2013 wishlist to include current state-of-the-art
- attempt to quantify the necessary precision for LHC13 processes considering specific observables
- identify key measurements and priorities

Results of discussion of wishlist

Request

- wiki contains first results from discussions at Les Houches
- theorists and in particular experimentalists are encouraged to update the wiki page
- would be very nice to have precision requirements for physical observables from experimentalists

General aspects

- specify the details of top decays: NWA, pole approximation
- should more processes be requested at NNLO + PS?

Input/questions for wishlist I

$\mathrm{H} + \text{jets}$

- Higgs p_{T}: resummation of NNLO needed ($\mathrm{N^3LL}$)
- jet veto: NNLO + resummation needed
- how important is full $m_{\mathrm{t}}/m_{\mathrm{b}}$ dependence at NNLO?
  in particular for boosted Higgs analyses, high p_{T}
- full m_{b} dependence more important for top/bottom interference at NNLO?
- QED $\times$ QCD at NNLO, accuracy of factorized ansatz?
  state of the art for high p_{T}, boosted analyses?
  estimates of missing corrections?
- accuracy of boosted Higgs analyses for $\mathrm{t\bar{t}H}$?

Input/questions for wishlist II

heavy quarks

- NNLO threshold resummation needed for top-mass measurements?

electroweak gauge bosons

- expected experimental accuracy for W mass measurements?
- resummation of $p_{\mathrm{T,W}}$ at N^{3}LL needed for W-mass measurements?
- N^{3}LL resummation needed for p_{T} and jet vetos in WW production

Outline

Propagation of NNLO results

Situation

- Complicated NNLO computations become available
- high CPU cost for generating events

Question

- How can the results of precision calculations efficiently be made available for flexible experimental analysis?

Options

- *N* tuples
- histograms
- HepMC format (as input for Rivet)

Quantifying cost of NNLO computations

planned investigation managed by Simon Badger

Attempt to compare CPU time / number of weighted events for sensible distributions for various components in

- $\mathrm{H}+\mathrm{j}$ with sector decomposition improved FKS subtraction
- $\mathrm{H}+\mathrm{j}/\mathrm{W}+\mathrm{j}$ with *N*-jettiness subtraction
- $\mathrm{H}+\mathrm{j}$ at NLO for low p_{T} ($0.5\,\mathrm{GeV}$) with SHERPA (as a contribution to inclusive Higgs)
- $\mathrm{WW}/\mathrm{ZZ}/\mathrm{Z}\gamma/\mathrm{W}\gamma/\gamma\gamma$ with q_{T} subtraction
- di-jets/$\mathrm{e}^+\mathrm{e}^- \to 3\mathrm{j}$ with antenna subtraction Glover/Gehrmann et al.
- $\mathrm{t}\bar{\mathrm{t}}$ with STRIPPER Czakon/Mitov et al.

try to estimate size of a basic root *N*-tuple format in these cases

Root Ntuples at NNLO

within the qT/NJettiness subtraction methods one can estimate the size of storing events using NLO +1j

contribution from Marek Schönherr

e.g. incl. H at NNLO (H+j at NLO with SHERPA)

estimated number of events to reach target accuracy of 0.1%

$$\sigma^{\mathrm{NNLO}} = 44\,\mathrm{pb}$$

$q_{T,\mathrm{cut}}$	α-dipole	#events	Ntuple size	$\sigma(q_T > q_{T,\mathrm{cut}})$
0.5	0.007	1.6×10^9	1.6 TB	-5.9 pb
1	0.007	0.8×10^9	0.8 TB	34.0 pb
1	1	0.4×10^9	0.4 TB	35.4 pb
2	0.007	0.4×10^9	0.4 TB	49.5 pb

convergence improved by tuning the phase space occupied by the counter-terms (α-dipole)

more stable for $q_T \sim$ 1-2GeV

NNLO *N*-tuple test case

Detailed study of *N* tuples for NNLO case

$e^+e^- \to 3$ jets with EERAD3

implement *N* tuples and investigate

- required event number / storage size
- appropriate format
- reweighting procedure for different scales

task force: Gudrun Heinrich, Daniel Maitre, Simon Badger

Outline

Summary

Described three Loops and Multilegs TH projects for Les Houches 2015

- comparison of NLO EW automated calculations
- update and priorities of high-precision wishlist
- study options for propagation of NNLO results

other Loops and Multilegs TH projects started here

- comparison of scale choices at fixed order for W + jets MINLO vs. $H_{\mathrm{T}}/2$
  Simon Badger, Daniel Maitre
- comparison of NNLO vs. LoopSim for W + jets
  Daniel Maitre, Frank Petriello

Summary continued

much more work needed for LHC13:

higher-order QCD: see introductory talk of Simon Badger

- NNLO beyond $2 \to 3$ requires a lot of work
- comparison between fixed order NNLO and NLO MC techniques

electroweak corrections

- combination with NNLO,... QCD corrections
- matching to parton showers including QED effects
- EW effects in PDFs (NNPDF2.3QED, other sets to come)
- NNLO QCD$\times$EW and NNLO EW corrections for precision observables
- treatment of final-state photons (see also subgroup: photon studies for direct photon measurements)