QCD and EW NLO corrections with NLOX

Effects in $bg \to Zb$

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Work in progress, with: S. Honeywell (FSU)
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LoopFest XV, University at Buffalo, August 16, 2016

1) Introducing NLOX

- A tool for automated NLO QCD and EW one-loop corrections in the SM

2) Prototype case $bg \to Zb$

- QCD and EW corrections
- Massive b effects

EW and QCD fixed-order NLO calculations with full mass dependence

Want to have as much control over the calculations as possible

NLOX had been around as a code for calculating QCD corrections to Wbb+jet
[L. Reina, T. Schutzmeier, 2012]

- Automatized calculation of NLO QCD corrections
- Loosely connected collection of scripts, to be handled with care for proper use

Revival of NLOX for $bg \to Zb$ (interesting prototype process to study EW and mass effects)
[L. Reina, S. Quackenbush]

- Bug fixing large parts
- Adding partial suport for EW corrections and masses
- Extending the tensor reduction library

Overhaul of NLOX for generic EW and QCD one-loop calculations up to $2 \to 4$
[S. Honeywell, L. Reina, CR, S. Quackenbush]

- Consistent setup for EW and QCD corrections
- Counterterms for QCD and EW renormalization
- User friendly interface
- Full control over input parameters

NLOX consists of three major parts, managed through the script `nlox.py`

- `diagen`: diagram generation and formatting via QGraf and Python
- `amptools`: diagram simplification and generation of squared amplitude via Python and Form
- `tred`: C++ library for numerical tensor reduction

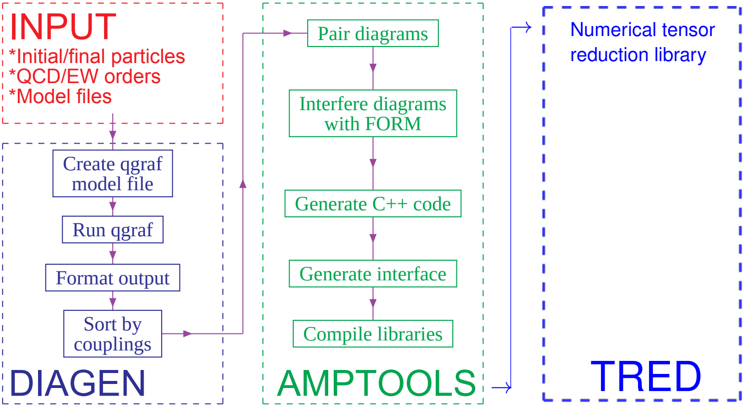


Image courtesy: S. Honeywell

NLOX has come a long way during the past year (mostly thanks to a very motivated student, S. Honeywell):

- Squared tree-level and one-loop matrix elements in the SM (helicity summed).
- 't Hooft-Feynman gauge, including scalar and pseudo-scalar unphysical degrees of freedom.
- UV and IR regularized using dim. regularization with $d = 4 - 2\varepsilon$.
- The one-loop MEs are automatically EW and QCD renormalized.
- QCD: on-shell renormalization for massive quarks; $\overline{\mathrm{MS}}$ for g_s, massless quarks and gluons.
- EW: on-shell renormalization [A. Denner, Fortschr.Phys.41:307-420,1993, new in arXiv:0709.1075].

Interface:

- User friendly Python interface, input-card based.
- CUBA-Vegas and LHAPDF interface for stand-alone external phase-space integration (of each piece).
- Flexible C++ interface
  - NLOX's building blocks can be interfaced with codes that do the NLO regularization (based on BLHA2).
  - NLOX's CUBA interface can be used to interface external Fortran or C++ code.

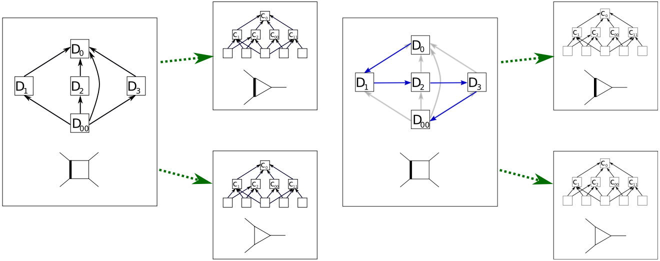
CUBA [T. Hahn, Comput. Phys. Commun. 168 (2005) 78]
LHAPDF6 [A. Buckley et al., 2014]

- What has changed mostly so far in the overhaul?
  - Gone from dis-connected collection of scripts to fully integrated package
  - Feynman rule model files fully extended to the SM
  - Automatized and simplified process setup, renormalization, etc.
  - Easy to use, OLP interface, etc.
- Coupling counting (diagen), in a given process
  - Produce QGraf model file from our own, and let it produce all possible tree- and one-loop diagrams.
  - Sort diagrams by their respective coupling powers in e and g_s, and store in diagram files (Python).
- Renormalization strategy (diagen)
  - Implemented vertex and propagator counterterms for QCD and almost all necessary EW ones.
  - From them build UV counterterm diagrams (QGraf, Python).
  - Consistent treatment of mass counterterm insertion, etc.
- Amptools
  - Produce all pairings of diagrams, collect those squared amplitudes that have the same coupling power (Python).
  - Simplify color structures, and evaluate (Form).
  - Simplify Dirac structres as much as possible (Form).
  - Collect terms belonging to the same Dirac string (standard-matrix-element; SME) (Form).
  - Generate C++ code in terms of SMEs, suitable for tred (Python).

Form [J.A.M.Vermaseren, math-ph/0010025]
QGraf [P. Nogueira, Journal of Computational Physics 105 (1993) 279-289.]

Tred

- Implements the Denner-Dittmaier reduction algorithm [Denner, Dittmaier, 2005] numerically, and
- Passarino-Veltamn reduction for 4-pt and lower. [Passarino, Veltman, 1979]
- [Diakonidis, Fleischer, et al., 2008] for 5-pt and higher.
- Building up a tree of possible scalar coefficients, compute their values (QCDLoop [Ellis, Zanderighi], LoopTools [T. Hahn]) as they are encountered and cache for reuse.

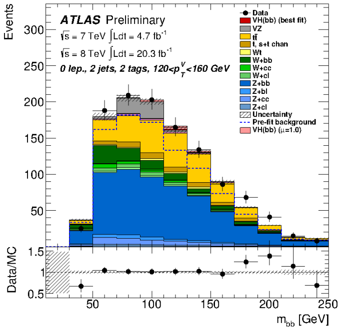


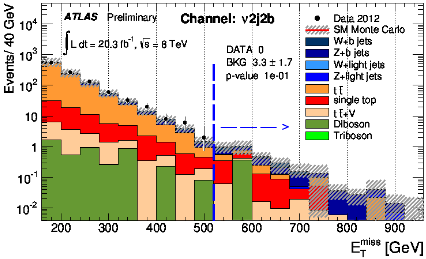
Validation

- Phase-space point comparison of large list of QCD corrected $2 \to 2$ and $2 \to 3$ processes vs. GoSam [Greiner et al.].
- Did not yet compare vs. other codes such as RECOLA [A. Denner, L. Hofer, J.-N. Lang, S. Uccirati] / Collier [A. Denner, S. Dittmaier, L. Hofer], or OpenLoops [F. Cascioli, P. Maierhoefer, S. Pozzorini] / Sherpa

$Z + b$-jet(s)

- Background to Higgs production:
  Impact on accuracy of Higgs coupling measurements.
- Background to new physics searches:
  Signals w/ heavy SM bosons in assoc. with t and b quarks.
- Direct b-quark PDF measurements:
  b-mass effects become relevant.
- b- vs. c-tagging efficiency 60% vs. 15%:
  Majority of tagged ZQ event are from Zb.





Upper left: [ATLAS-CONF-2013-079]

Lower left: [ATLAS-CONF-2014-006]

- How to treat the b quark in theory calculations?
- 5FS
  - LO at $O(\alpha_s\alpha)$ via $bg \to Zb$
  - Initial-state b with full b-mass dependence is theoretically challenging in an NLO calculation
- 4FS
  - LO at $O(\alpha_s^2\alpha)$ via $gg \to Zb\bar{b}$ (dominant), $q\bar{q} \to Zb\bar{b}$, ...
  - Initial-state $g \to b\bar{b}$ explicit in the FO
  - Massive final-state b quarks
- Only a matter of re-arranging the perturbative series?
  - Increasing interest to study the effects of 5FS vs. 4FS
  - Observable differences in various Xsec predictions

Cross section	Measured	MADGRAPH (5F)	aMCATNLO (5F)	MCFM (parton level)	MADGRAPH (4F)	aMCATNLO (4F)
σ_{Z+1b} (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.22	$3.70^{+0.23}_{-0.26}$	$3.03^{+0.30}_{-0.36}$	$3.11^{+0.47}_{-0.81}$	$2.36^{+0.47}_{-0.37}$
σ_{Z+2b} (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.07	$0.29^{+0.04}_{-0.04}$	$0.29^{+0.04}_{-0.04}$	$0.38^{+0.06}_{-0.10}$	$0.35^{+0.08}_{-0.06}$
σ_{Z+b} (pb)	$3.88 \pm 0.02 \pm 0.22$	4.03 ± 0.24	$3.99^{+0.25}_{-0.29}$	$3.23^{+0.34}_{-0.40}$	$3.49^{+0.52}_{-0.91}$	$2.71^{+0.52}_{-0.41}$
$\sigma_{Z+b/Z+j}$ (%)	$5.15 \pm 0.03 \pm 0.25$	5.35 ± 0.11	$5.38^{+0.34}_{-0.39}$	$4.75^{+0.24}_{-0.27}$	$4.63^{+0.69}_{-1.21}$	$3.65^{+0.70}_{-0.55}$

e.g. [CMS, 1402.1521, 1310.1349]

- ACOT scheme [Collins, Tung] (massive factorization) traded vs. simplified version ...
- S-ACOT [Soper, Olnes, Kraemer, 2000] resum the the leading mass logarithms in the PDF. Coefficient functions have no mass dependence. Estimated error $\propto m_b^2/Q^2$
- It is not too crazy to look at the full mass effects in a 5FS, though!

Treat the b quark massive in the initial state

- For a consistent combination with realistic parton-shower MCs in the 5FS need consistent treatment of initial- and final-state masses
- More generally, in any method that algorithmically generates higher orders from tree-level processes
  - For example $gg \to Zb\bar{b}$ (an $O(\alpha_s^2\alpha)$ real correction to $bg \to Zb$) with a massive b cannot be generated from $bg \to Zb$ with a massless b, by convoluting with the splitting function for $g \to b\bar{b}$
- Can be treated in phase-space slicing (in-house codes by S. Honeywell, L. Reina, D. Wackeroth) [Harris,Owens]
- With another student (D. Figueroa) we started to look at massive initial-state dipoles (it's basically all there [Dittmaier, 1999] [Catani, Dittmaier, Seymour, Trocsanyi]; [Nagy, Soper], [Robens, Chung, Kraemer])

What else is there to look at while we're at it anyway?

- For LHC run II, knowledge of NLO EW (and NNLO QCD) corrections mandatory
- EW effects become also important for a consistent combination with realistic parton-shower MCs

$Z + b$-jet(s) production offers a good prototype case to study both, mass effects and impact of EW physics

- Lowest order process: $bg \to Zb$ at $O(\alpha_s \alpha)$
- NLO QCD correction known [Campbell, Ellis, Maltoni, Willenbrock, 2004; MCFM]
  - Initial state b in the ME massless; b PDF in the S-ACOT scheme
  - Inclusive NLO QCD corrections add ∼20% to the LO prediction
- NLO EW becoming increasingly important at higher energies, for processes relevant to LHC run II (both, NNLO QCD and NLO EW can have the same impact)
- Mass effects and EW corrections can be *a priori* of comparable size, and, even if small, both need to be accounted for in precision predictions

- NLO EW and QCD corrections to $bg \to Zb$, with full b-mass dependence
  - Well defined set of NLO corrections in a well defined FS
  - Consistent estimate of the impact of EW corrections and mass effects on $Z+b$-jet(s) production possible
  - direct impact on b PDF determinations

1) The impact of mass effects on the fixed-order total Xsec and distributions can be studied in the comparison of massless and massive NLO QCD corrections
2) The impact of EW corrections on the fixed-order total Xsec and distributions can be studied in the comparison of $O(\alpha_s^2 \alpha)$ and $O(\alpha_s \alpha^2)$ with full b-mass dependence

- At this stage, in addition to dedicated ME in-house codes for $bg \to Zb$ also wanted to have an automated tool, to provide all necessary hard ingredients
  - NLOX: Existed in a preliminary state as tool(s) for the computation of QCD one-loop corrections
  - Revived: Wanted to have a tool to compute the QCD and EW one-loop corrections with full mass effect

LO Xsec for $Z+b$-jet(s) production in 5FS

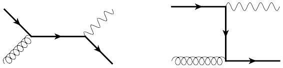
$\sigma_{LO} = \alpha_s \alpha \sigma_{LO}^{(1,1)} + \alpha^2 \sigma_{LO}^{(0,2)}$

NLO Xsec for $Z+b$-jet(s) production

$\sigma_{NLO} = \alpha_s^2 \alpha \sigma_{NLO}^{(2,1)} + \alpha_s \alpha^2 \sigma_{NLO}^{(1,2)} + \alpha^3 \sigma_{NLO}^{(0,3)}$

- $\sigma_{LO}^{(1,1)}$: $bg \to Zb$
- $\sigma_{LO}^{(0,2)}$: $b\gamma \to Zb$: negligible due to small γ PDF (Xsec $O(5k)$ smaller than for $bg \to Zb$)
- $\sigma_{NLO}^{(0,3)}$: negligible for the same reason (the γ PDF itself is suppressed by $O(200)$ vs. the g PDF)
- $\sigma_{NLO}^{(2,1)}$: known for massless b

$bg \to Zb$ Born: tree-level s- and t-channel



$bg \to Zb$ QCD NLO:

- virtual: 13 loop diagrams
- real (for $\geq 1\,b$-jet): gluon radiation from tree-level s- and t-channel, and new channels gg, $b\bar{b}$, $b\bar{q}$, $q\bar{q}$
- $b\bar{b}$ has no singularities and is negligible due to $2\times b$ PDF

$bg \to Zb$ EW NLO:

- virtual: one-loop exchange of EW gauge bosons and scalars (88 loop diagrams)
- real: emission of EW gauge bosons and scalars
  - only the QED corrections have IR singularities (soft) and need to be included to cancel the virtual singularities
  - W emission is CKM suppressed
  - Z/H emissions are finite and will be considered separately; they have a distinct signature and, depending on the experimental setup, need not necessarily be considered in the incl. Xsec for $Z+b$-jet(s)

Virtual corrections:

- NLOX

Real emission:

- The QED real corrections relevant to us consist of single γ emission from a massive b quark
  - soft IR divergencies ($E_\gamma \to 0$)
  - regulated through a phase-space slicing method with a single soft slicing parameter δ_s
  - new: soft integrals due to γ emission from initial-state massive b quarks
  - independence of δ_s has been checked in the $[10^{-6}, 10^{-3}]$ range (in units of $\sqrt{\hat{s}}/2$)
- QCD
  - so far: real gluon emission using a phase-space slicing with a soft and a collinear slicing parameter, δ_s and δ_c
  - the soft region involves new phase-space integrals again
  - coll. singularities are coming from radiating off the intial-state gluon and are absorbed into the PDF

Both for EW and QCD:

- Real emission: in-house PS slicing implementations and real MEs (L. Reina, D. Wackeroth, S. Honeywell)
- Virtual: in-house (L. Reina, D. Wackeroth, S. Honeywell) to cross-check vs. NLOX
- External PS integration: in-house routines (in-house Vegas implementations or CUBA-Vegas) to cross-check vs. NLOX CUBA integration

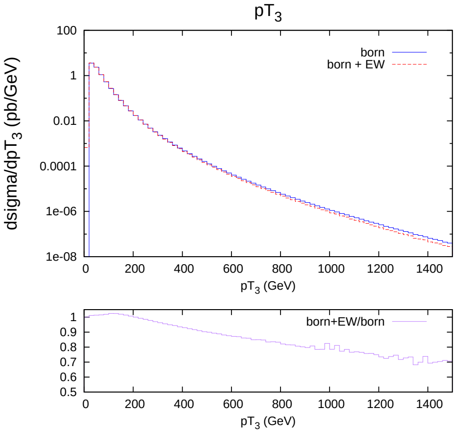
Hadron momenta in the lab frame (hadronic CMS): $P_A = \frac{\sqrt{S}}{2}(1,0,0,+1) \to f_A(x_1)$
$P_B = \frac{\sqrt{S}}{2}(1,0,0,-1) \to f_B(x_2)$

Light-cone parametrization: $p_1 = x_1 P_A + \frac{m_1^2}{x_1 x_2 S} x_2 P_B \quad \to \quad p_1^2 = m_1^2$ ($p_1 = x_1 P_A$ if $m_1 \to 0$)
$p_2 = x_2 P_B + \frac{m_2^2}{x_1 x_2 S} x_1 P_A \quad \to \quad p_2^2 = m_2^2$ ($p_2 = x_2 P_B$ if $m_2 \to 0$)

- For example $p_1 = \bar{p}_b$, $p_2 = \bar{p}_g$, where $\bar{p}_i$ parton momenta in hadronic CMS.
- Boosting them into the partonic CMS, one derives
  $m_b < p_b^0 < \frac{\sqrt{S}}{2}$,
  $\frac{m_b}{\sqrt{S}} < x_1 < \frac{1}{2} + \frac{1}{2}\sqrt{1-4(m_b^2/S)}$
  $0 < x_2 < 1$ as usual

See also
[Nagy, Soper, 2014]
They argue that for a proper treatment in combination with showers you have to define the PDFs with massive splitting kernels

[Collins]



EW corrections.
Massive b, light-cone parametrization.

- Born: (162.75831 ± 0.00525) pb
- Soft real: $(-1.68578142 \pm 1.421 \times 10^{-04})$ pb
- Hard real: $(1.19336891 \pm 1.969 \times 10^{-04})$ pb
- Virtual: $(1.59674454 \pm 2.418 \times 10^{-04})$ pb
- Total: 164.96698 pb

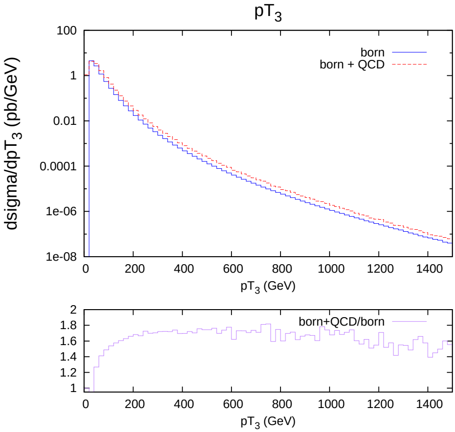
p_T(b-jet) > 25 GeV
|rap(b-jet)| < 2.5
PDF set = CT14nlo
Fixed scale: MZ
$\sqrt(s) = 13$ TeV

$p_\perp$ of the Z

Virtuals: NLOX

Real: S. Honeywell

m_b = 4.75 GeV
M_Z = 91.1876 GeV
M_W = 80.385 GeV
α_e = 1/137.035999074
$\alpha_s(M_Z)$ = 0.118



QCD corrections (for comparison).
Massless b (MCFM; S-ACOT).

Also tested the PDF parametrizations at the Born level

(massless, naive)
190.472 +/- 0.006 pb

(massive, naive)
189.071 +/- 0.006 pb

(massive, lightcone)
162.758 +/- 0.005 pb

$p_\perp$ of the Z

- Re-introducing NLOX as auotmated tool for QCD and EW NLO corrections.
- Studying Z+jet(s) with heavy partons: $bg \to Zb$
- EW corrections and effects of massive b (intial state!)
- Computation of $bg \to Zb$ (almost) completed with in-house codes and also using NLOX
- First preliminary results for $bg \to Zb$ (QCD and EW), with massive b
- Started working on massive dipoles

Work in progress

- Complete implementation of EW counterterms to continue with Zbb
- Increase efficiency (at the moment we are operating at a certain baseline):
- Finish the OLP interface and start testing with Monte Carlo event generators
- Add to the reduction library
- Add to the accuracy checks

THANK YOU