Automation of EW corrections with NLOX

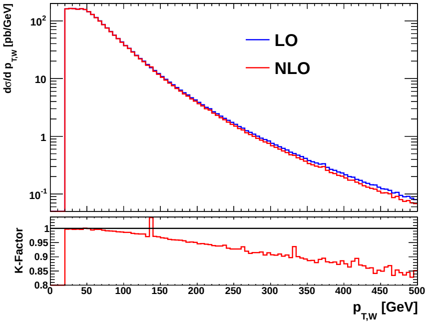
– status and update –

Christian Reuschle
CREUSCHLE@HEP.FSU.EDU

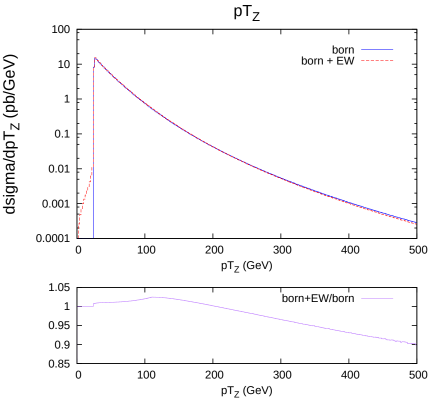
Florida State University
Physics Department
HEP Theory Group

LoopFest XVI, Argonne National Lab, June 2, 2017

Importance of EW corrections



- $p_\perp$ of the W in W+2 jets production: -15% EW correction at 500GeV. [Chiesa, Greiner, Tramontano, arXiv:1507.08579]
- VBs + jets important final states in searches for NP and Higgs precision studies.
- EW corrections become important in high-energy tails of distributions, where also NP effects are expected.



- $p_\perp$ distribution of the Z in $bg \to Zb$. -10% EW correction at 500GeV: [S. Honeywell, PhD thesis]
- Virtual: NLOX+Cuba.
  Real: PS slicing in-house code.

- NLO revolution, past 10-15 years:

  Automation of NLO QCD corrections. Breakthroughs in understanding underlying principles & implementation of efficient algorithms. NLO QCD corrections for virtually all SM processes "at the push of a button".

- Paradigm shift:

  Dedicated ME providers (OLPs for one-loop providers) & event generators are interfaced on the code level.

- This trend continues in the EW direction:

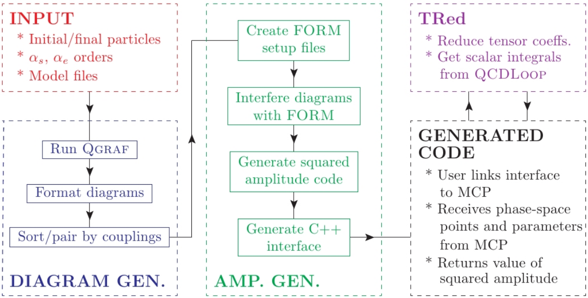
  Many of the automated ME providers have extended their range of applicability to the automation of EW corrections.

  - [OpenLoops (+Sherpa,+Munich)]: W+jets [Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr, arXiv:1412.5157], V+jets (off-shell) + jet merging [Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr, arXiv:1511.08692].
  - [Recola]: Z+2 jets (off-shell) [Denner, Hofer, Scharf, Uccirati, arXiv:1411.0916], (+Sherpa): Z+jets, $t\bar{t}$+H [Biedermann, Bräuer, Denner, Pellen, Schumann, Thompson, arXiv:1704.05783].
  - [GoSam (+MadDipole)]: W+2 jets [Chiesa, Greiner, Tramontano, arXiv:1507.08579].
  - [MG5_aMC@NLO]: $t\bar{t}$+H [Frixione, Hirschi, Pagani, Shao, Zaro, arXiv:1407.0823], $t\bar{t}$+V [Frixione, Hirschi, Pagani, Shao, Zaro, arXiv:1504.0344].

NLOX: Automated EW & QCD+EW one-loop corrections

Code development: [S. Honeywell, S. Quackenbush, L. Reina, CR]

- NLOX (NLO X-Sections): Early version applied in QCD corrections to $Wb\bar{b}$+jet [Reina, Schutzmeier, arXiv:1110.4438]
- Introduced as code for automated one-loop EW corrections at last year's LoopFest; Prototype process: EW corrections to $bg \to Zb$ [Honeywell, Quackenbush, Reina, CR, Wackeroth]
- Color- and helicity-summed tree-level and one-loop matrix elements in the SM
- Approach based on Feynman diagrams; Consistent setup for EW and QCD corrections; Counterterms for QCD and EW renormalization; User friendly interface; Full control over input parameters
- Three major parts: Python master script `nlox.py`
  - Diagram generation, formatting and coupling sorting: Python, QGraf
  - Simplification and generation of the squared amplitude: Python, Form
  - Generation of compilable C++ ME code; linked to a custom made C++ tensor reduction library TRED



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

- Color-and helicity-summed tree-level and one-loop matrix elements in the SM.
- 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:

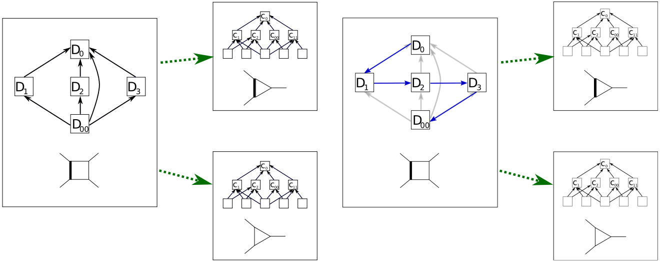
- User friendly Python interface, input-card based.
- CUBA-Vegas and LHAPDF interface for stand-alone external phase-space integration (of each piece).
- Flexible C++ interface
  - NLOX's building blocks can be interfaced with event generators codes (based on BLHA2).
  - NLOX's CUBA interface can be used to interface external Fortran or C++ code.
- Feynman diagram generator (can be very useful)
- Dedicated interface to Recola for easy PSP and X-Section level cross checks

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

- What has changed mostly so far in the overhaul?
  - Model files fully extended to the SM (dedicate model for massless and massive b's)
  - Automatized and simplified process setup, renormalization, etc.
  - Easy to use, OLP interface, etc.
- Coupling counting in a given process (diagram level)
  - 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
  - Implemented vertex and propagator counterterms for QCD and EW corrections.
  - From them build UV counterterm diagrams (QGraf, Python).
  - Consistent treatment of mass counterterm insertion, etc.
- Squared amplitude level
  - Produce all pairings of diagrams, collect those with the same coupling power (Python).
  - Simplify color structures, and evaluate (Form).
  - Simplify Dirac structures 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.]

- Denner-Dittmaier reduction [Denner, Dittmaier, 2005] and and Passarino-Veltman reduction [Passarino, Veltman, 1979] for 4-pt and lower
- [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.



Taken from [S. Honeywell, PhD thesis]; Please excuse the unreferenced Table

$u\bar{u} \to gd\bar{d}$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola	GoSam
Born	$\mathcal{O}(\alpha_s^3)$	0.0002395500956426763	0.2395500956426763E-03	0.2395500956426703E-03
C_2/Born	$\mathcal{O}(\alpha_s^4)$	-8.33333333333333	-8.333333333333334	-8.333333333333364
C_1/Born	$\mathcal{O}(\alpha_s^4)$	-26.99462578393458	-26.99462578393448	-26.99462578393469
C_0/Born	$\mathcal{O}(\alpha_s^4)$	-12.54030184367164	-12.54030184402130	-12.54030184402180

$d\bar{d} \to ggg$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola	GoSam
Born	$\mathcal{O}(\alpha_s^3)$	0.0003988730682111007	0.3988730682111019E-03	0.3988730682110958E-03
C_2/Born	$\mathcal{O}(\alpha_s^4)$	-11.66666666666669	-11.66666666666666	-11.66666666666666
C_1/Born	$\mathcal{O}(\alpha_s^4)$	-31.36144638199454	-31.36144638199465	-31.36144638199454
C_0/Born	$\mathcal{O}(\alpha_s^4)$	-10.53030240397284	-10.53030240070475	-10.53030240070376

$gg \to \gamma t\bar{t}$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola	GoSam
Born	$\mathcal{O}(\alpha_s^2\alpha_e)$	3.024916410519366e-05	0.3024916410519305E-04	0.3024916410293219E-04
C_2/Born	$\mathcal{O}(\alpha_s^3\alpha_e)$	-5.999999999999964	-5.999999999999995	-6.000000000000009
C_1/Born	$\mathcal{O}(\alpha_s^3\alpha_e)$	-10.80787429465499	-10.80787429465735	-10.80787429465584
C_0/Born	$\mathcal{O}(\alpha_s^3\alpha_e)$	17.50169288566857	17.50169288601501	17.50169288601839

PSP Comparisons of QCD corrections

Taken from [S. Honeywell, PhD thesis]; Please excuse the unreferenced Table

$gg \to Zt\bar{t}$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola	GoSam
Born	$\mathcal{O}(\alpha_s^2\alpha_e)$	2.363537682652218e-05	0.2363537682652213E-04	0.2363537682475561E-04
C_2/Born	$\mathcal{O}(\alpha_s^3\alpha_e)$	-5.999999999999993	-5.999999999999899	-5.999999999999999
C_1/Born	$\mathcal{O}(\alpha_s^3\alpha_e)$	-11.41373063878653	-11.41373063878616	-11.41373063878679
C_0/Born	$\mathcal{O}(\alpha_s^3\alpha_e)$	15.2795846726314	15.27958468234513	15.27958468234574

$gg \to ht\bar{t}$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola
Born	$\mathcal{O}(\alpha_s^2\alpha_e)$	7.262058203129514e-05	0.7262058203129505E-04
C_2/Born	$\mathcal{O}(\alpha_s^3\alpha_e)$	-5.999999999485391	-5.999999999997610
C_1/Born	$\mathcal{O}(\alpha_s^3\alpha_e)$	-10.02836976769005	-10.02836976685641
C_0/Born	$\mathcal{O}(\alpha_s^3\alpha_e)$	15.78425523713124	15.78425527587955

$u\bar{u} \to ht\bar{t}$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola
Born	$\mathcal{O}(\alpha_s^2\alpha_e)$	0.0002461124726272914	0.2461124726272914E-03
C_2/Born	$\mathcal{O}(\alpha_s^3\alpha_e)$	-2.666666666665627	-2.666666666667972
C_1/Born	$\mathcal{O}(\alpha_s^3\alpha_e)$	-6.039884630087075	-6.039884630094701
C_0/Born	$\mathcal{O}(\alpha_s^3\alpha_e)$	-5.439276782800005	-5.439276733811660

PSP Comparisons of QCD corrections

Taken from [S. Honeywell, PhD thesis]; Please excuse the unreferenced Table

$u\bar{u} \to d\bar{d}c\bar{c}$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola	GoSam
Born	$\mathcal{O}(\alpha_s^4)$	2.077641357247545e-09	0.2077641357247536E-08	0.2077641357247527E-08
C_2/Born	$\mathcal{O}(\alpha_s^5)$	-7.999999999993321	-7.999999999922142	-8.000000000000178
C_1/Born	$\mathcal{O}(\alpha_s^5)$	-30.52739031171835	-30.52739031191933	-30.52739031179023
C_0/Born	$\mathcal{O}(\alpha_s^5)$	-33.31088743962901	-33.31088744061343	-33.31088744066471

$u\bar{u} \to b\bar{b}t\bar{t}$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola	GoSam
Born	$\mathcal{O}(\alpha_s^4)$	2.974551724275585e-09	0.2974551724275587E-08	0.2974551724275582E-08
C_2/Born	$\mathcal{O}(\alpha_s^5)$	-5.333333333332101	-5.333333333402811	-5.333333333333529
C_1/Born	$\mathcal{O}(\alpha_s^5)$	-24.27352487555908	-24.27352487545107	-24.27352487556620
C_0/Born	$\mathcal{O}(\alpha_s^5)$	-10.40556283358706	-10.40556283286741	-10.40556283283043

$gg \to b\bar{b}t\bar{t}$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola	GoSam
Born	$\mathcal{O}(\alpha_s^4)$	7.857420029449179e-08	0.7857420029449088E-07	0.7857420029449035E-07
C_2/Born	$\mathcal{O}(\alpha_s^5)$	-8.666666666664934	-8.666666666666629	-8.666666666666680
C_1/Born	$\mathcal{O}(\alpha_s^5)$	-39.41725719694034	-39.41725719694504	-39.41725719694475
C_0/Born	$\mathcal{O}(\alpha_s^5)$	-37.3170130240437	-37.31701302651476	-37.31701302651134

PSP Comparisons of QCD corrections

Taken from [S. Honeywell, PhD thesis]; Please excuse the unreferenced Table

$u\bar{d} \to e^+ \nu_e b\bar{b}$, with massive b-quarks, using the phase-space point in Table (**??**)

	Order	NLOX	Recola
Born	$\mathcal{O}(\alpha_s^4)$	1.608131398006336e-08	0.1608131398006333E-07
C_2/Born	$\mathcal{O}(\alpha_s^5)$	-2.666666666666688	-2.666666666666678
C_1/Born	$\mathcal{O}(\alpha_s^5)$	8.217747261112551	8.217747261112734
C_0/Born	$\mathcal{O}(\alpha_s^5)$	149.1755722528422	149.1755722612493

Taken from [S. Honeywell, PhD thesis]; Please excuse the unreferenced Table

$bg \to Zb$, with massive b-quarks, using the phase-space point in Table (**??**)

	Order	NLOX	Recola
Born	$\mathcal{O}(\alpha_s \alpha_e)$	0.3988902360788524	0.3988902360788524
C_2/Born	$\mathcal{O}(\alpha_s \alpha_e^2)$	0	0
C_1/Born	$\mathcal{O}(\alpha_s \alpha_e^2)$	-2.545063259569829	-2.545063259569986
C_0/Born	$\mathcal{O}(\alpha_s \alpha_e^2)$	-66.0545642251593	-66.05456422513492

$e^+e^- \to \mu^+\mu^-$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola
Born	$\mathcal{O}(\alpha_e^2)$	2.119697435758658	2.119697435758659
C_2/Born	$\mathcal{O}(\alpha_e^3)$	-3.999999999999994	-4.000000000000001
C_1/Born	$\mathcal{O}(\alpha_e^3)$	-18.9972544944435	-18.99725449444341
C_0/Born	$\mathcal{O}(\alpha_e^3)$	-58.36143453973728	-58.36143454099178

$e^+\nu_e \to \mu^+\nu_\mu$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola
Born	$\mathcal{O}(\alpha_e^2)$	2.870541871568103	2.870541871568101
C_2/Born	$\mathcal{O}(\alpha_e^3)$	-2	-1.999999999999978
C_1/Born	$\mathcal{O}(\alpha_e^3)$	-14.55516676511649	-14.55516676511632
C_0/Born	$\mathcal{O}(\alpha_e^3)$	-162.0819110836235	-162.0819110877675

PSP Comparisons of EW corrections

Taken from [S. Honeywell, PhD thesis]; Please excuse the unreferenced Table

$\nu_e \bar{\nu}_e \to \nu_\mu \bar{\nu}_\mu$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola
Born	$\mathcal{O}(\alpha_e^2)$	1.2072084184728	1.207208418472800
C_2/Born	$\mathcal{O}(\alpha_e^3)$	0	0
C_1/Born	$\mathcal{O}(\alpha_e^3)$	-8.888888888888962	-8.888888888888832
C_0/Born	$\mathcal{O}(\alpha_e^3)$	-95.3768727871602	-95.37687278933537

$\nu_e \bar{\nu}_e \to ZZ$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola
Born	$\mathcal{O}(\alpha_e^2)$	2.857891640385139	2.857891640385161
C_2/Born	$\mathcal{O}(\alpha_e^3)$	0	0
C_1/Born	$\mathcal{O}(\alpha_e^3)$	-8.888888888888962	-8.888888888888889
C_0/Born	$\mathcal{O}(\alpha_e^3)$	-169.4628850895685	-169.4628850900768

$e^- \gamma \to e^- \gamma$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola
Born	$\mathcal{O}(\alpha_e^2)$	4.188796953987349	4.188796953987348
C_2/Born	$\mathcal{O}(\alpha_e^3)$	-1.999999999999997	-2.000000000000012
C_1/Born	$\mathcal{O}(\alpha_e^3)$	-5.666277876227508	-5.666277876227587
C_0/Born	$\mathcal{O}(\alpha_e^3)$	-32.89198944630831	-32.89198944535889

PSP Comparisons of EW corrections

Taken from [S. Honeywell, PhD thesis]; Please excuse the unreferenced Table

$ug \to \gamma u$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola
Born	$\mathcal{O}(\alpha_s \alpha_e)$	0.6009746489741862	0.6009746489741863
C_2/Born	$\mathcal{O}(\alpha_s \alpha_e^2)$	-0.8888888888888878	-0.8888888888888831
C_1/Born	$\mathcal{O}(\alpha_s \alpha_e^2)$	-1.605375588200102	-1.605375588200088
C_0/Born	$\mathcal{O}(\alpha_s \alpha_e^2)$	-15.28911262100006	-15.28911262125787

$e^- \gamma \to e^- \gamma\gamma$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola
Born	$\mathcal{O}(\alpha_e^3)$	0.0001235020533276412	0.1235020533276406E-03
C_2/Born	$\mathcal{O}(\alpha_e^4)$	-1.999999999999973	-2.000000000000361
C_1/Born	$\mathcal{O}(\alpha_e^4)$	-8.454565275611175	-8.454565275608633
C_0/Born	$\mathcal{O}(\alpha_e^4)$	-161.9278766391825	-161.9278765681010

$\nu_e \bar{\nu}_e \to Z \nu_\mu \bar{\nu}_\mu$, using the phase-space point in Table (**??**)

	Order	NLOX	Recola
Born	$\mathcal{O}(\alpha_e^3)$	0.0005717565235318755	0.5717565235318735E-03
C_2/Born	$\mathcal{O}(\alpha_e^4)$	0	0
C_1/Born	$\mathcal{O}(\alpha_e^4)$	-13.3333333333334	-13.33333333333350
C_0/Born	$\mathcal{O}(\alpha_e^4)$	-170.5905674296937	-170.5905674451609

PSP Comparisons of EW corrections

Taken from [S. Honeywell, PhD thesis]; Please excuse the unreferenced Table

$\nu_e\bar{\nu}_e \to \nu_\mu\bar{\nu}_\mu\nu_\tau\bar{\nu}_\tau$, using the phase-space point in Table (**??**)

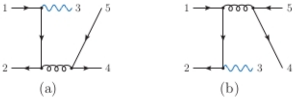
	Order	NLOX	Recola
Born	$\mathcal{O}(\alpha_e^4)$	3.551592719063201e-08	0.3551592719063195E-07
C_2/Born	$\mathcal{O}(\alpha_e^5)$	0	0
C_1/Born	$\mathcal{O}(\alpha_e^5)$	-17.7777777777776	-17.77777777777923
C_0/Born	$\mathcal{O}(\alpha_e^5)$	-231.0050069559277	-231.0050069682861

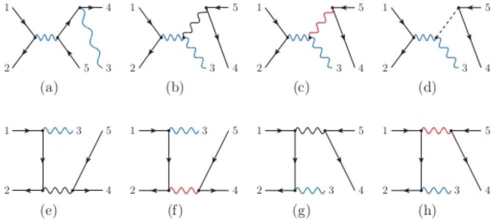
NLOX PROOF OF CONCEPT: $Wb\bar{b}$

Preliminary [S. Honeywell, S. Quackenbush, L. Reina, CR, D. Wackeroth]

- W+jets is an important process, e.g. in the search for NP
- EW corrections need to be included alongside QCD corrections
- As a proof of concept for NLOX we choose W+b-jets

$$\sigma = \sum_{n,m} \alpha_s{}^n \alpha_e{}^m \sigma_{n,m}, \quad \alpha_s = \frac{g^2}{4\pi}, \quad \alpha_e = \frac{e^2}{4\pi}$$





- Lowest orders:

  $\alpha_s^2\alpha_e^1 \qquad \alpha_s^1\alpha_e^2 \qquad \alpha_s^0\alpha_e^3$

- $\alpha_s^1\alpha_e^2 \hat{=} g^2e^1 \times g^0e^3 + cc$

  all zero due to color

- $\alpha_s^0\alpha_e^3 \hat{=} |g^0e^3|^2$

  not considered, due to α_e^3 suppression

- Only keep $\alpha_s^2\alpha_e^1 \hat{=} |g^2e^1|^2$
- Just $u\bar{d}$ and $\bar{d}u$ initial state for now

Preliminary [S. Honeywell, S. Quackenbush, L. Reina, CR, D. Wackeroth]

One-loop level

g^0e^5 (no virtual gluons) — 1084 diagrams

g^4e1 (no virtual EW VBs) — 37 diagrams diagrams

g^2e^3 (mixed) — 193 diagrams

Squared amplitude level

$\alpha_s^0\alpha_e^4 = g^0e^3$ tree $\times g^0e^5$ loop not considered due to α_e^4 suppression

$\alpha_s^1\alpha_e^3 = g^2e^1$ tree $\times g^0e^5$ loop all zero due to color

$\alpha_s^1\alpha_e^3 = g^0e^3$ tree $\times g^2e^3$ loop some color zeros, rest α_e^3 suppressed

$\alpha_s^2\alpha_e^2 = g^0e^3$ tree $\times g^4e^1$ loop some color zeros, but not all

$\alpha_s^2\alpha_e^2 = g^2e^1$ tree $\times g^2e^3$ loop some color zeros, but not all

$\alpha_s^3\alpha_e^1 = g^2e^1$ tree $\times g^4e^1$ loop pure QCD virtual correction

We only keep $\alpha_s^2\alpha_e^2$ and $\alpha_s^3\alpha_e^1$

NLOX PROOF OF CONCEPT: $Wb\bar{b}$ AT NLO REAL

Preliminary [S. Honeywell, S. Quackenbush, L. Reina, CR, D. Wackeroth]

Diagram level, e.g

(i) $u\bar{d} \to W^+ b\bar{b}g,\ g^3e^1$

(ii) $u\bar{d} \to W^+ b\bar{b}\gamma,\ g^2e^2$

(iii) $u\bar{d} \to W^+ b\bar{b}g,\ g^1e^3$

(iv) $u\bar{d} \to W^+ b\bar{b}\gamma,\ g^0e^4$

Squared amplitude level

$$\underbrace{|(\text{iv})|^2}_{\{n,m\}=\{0,4\}} + \underbrace{\left((\text{ii})(\text{iv})^* + (\text{iv})(\text{ii})^*\right)}_{\{n,m\}=\{1,3\}} + \underbrace{|(\text{ii})|^2}_{\{n,m\}=\{2,2\}}$$

α_e^4 suppressed; color zero

$$\underbrace{|(\text{iii})|^2}_{\{n,m\}=\{1,3\}} + \underbrace{\left((\text{i})(\text{iii})^* + (\text{iii})(\text{i})^*\right)}_{\{n,m\}=\{2,2\}} + \underbrace{|(\text{i})|^2}_{\{n,m\}=\{3,1\}}$$

α_e^3 suppressed

Diagram level, e.g

(i') $ug \to W^+ b\bar{b}d,\ g^3e^1$

(ii') $u\gamma \to W^+ b\bar{b}d,\ g^2e^2$

(iii') $ug \to W^+ b\bar{b}d,\ g^1e^3$

(iv') $u\gamma \to W^+ b\bar{b}d,\ g^0e^4$

Squared amplitude level

$$\underbrace{|(\text{iv}')|^2}_{\{n,m\}=\{0,4\}} + \underbrace{\left((\text{ii}')(\text{iv}')^* + (\text{iv}')(\text{ii}')^*\right)}_{\{n,m\}=\{1,3\}} + \underbrace{|(\text{ii}')|^2}_{\{n,m\}=\{2,2\}}$$

α_e^4 suppressed; color zero

$$\underbrace{|(\text{iii}')|^2}_{\{n,m\}=\{1,3\}} + \underbrace{\left((\text{i}')(\text{iii}')^* + (\text{iii}')(\text{i}')^*\right)}_{\{n,m\}=\{2,2\}} + \underbrace{|(\text{i}')|^2}_{\{n,m\}=\{3,1\}}$$

α_e^3 suppressed

Only keep $\alpha_s^2\alpha_e^2$ and $\alpha_s^3\alpha_e^1$ & no γ-induced processes & no heavy VB radiation

NLOX PROOF OF CONCEPT: $Wb\bar{b}$ COMPUTATIONAL SETUP

Preliminary [S. Honeywell, S. Quackenbush, L. Reina, CR, D. Wackeroth]

- Virtual & Born with NLOX+Cuba
- Real with dedicated two-cutoff PS slicing code
  (hard-coded MEs, historically cross-checked vs MG MEs, NLOX can also produce them)
- Combination of results on histogram level
- Soft and collinear contributions:
  Soft gluon-emission needs color-correlated Born MEs, with contribution $g^2e^1 \times g^0e^3 + cc$
  They are not zero, but small, so we drop them $\Rightarrow \alpha_s^2\alpha_e^2$ real only from γ-emission

```
mb = 4.75;     mt = 173;
mW = 80.385;   mZ = 91.1876;
mH = 125;      mu = mW+2.*mb;

// alpha_s(89.885) of CT14
alpha_s = 0.118257234682858 27;
g = sqrt(4.*PI*alpha_s);

// alpha_e(0) = 0.00729735256981 6315
alpha_e = 1./137.035999074;
e = sqrt(4.*PI*alpha_e);
```

- CT14qed_inc_proton.00.pds
- Diagonal CKM.

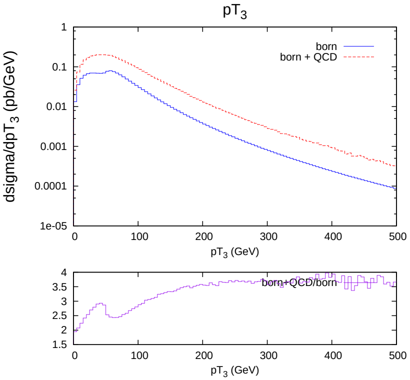
- Technical resonance cuts with $\delta_r = 0.25$ GeV:

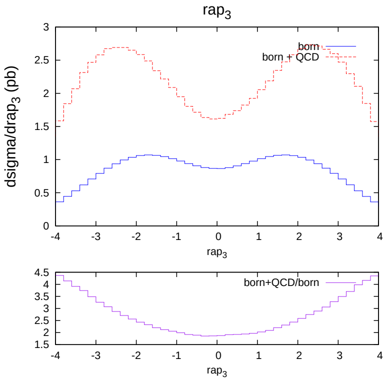
$$m_t - \delta_r < \sqrt{|(p_W + p_b)^2|} < m_t + \delta_r$$
$$m_h - \delta_r < \sqrt{|(p_b + p_b)^2|} < m_h + \delta_r$$
$$m_Z - \delta_r < \sqrt{|(p_b + p_b)^2|} < m_Z + \delta_r$$

- PS slicing cuts: $\delta_s = $1e-3 and $\delta_c = $1e-4.
- $p_{\perp,\min}^{b/\bar{b}} = 25$ GeV and $|\eta^{b/\bar{b}}|_{\max} = 2.5$.
- Simple separation of b and $\bar{b}$ with $\Delta R_{\min} = 0.4$.
- Simple recombination of g's and γ's with b's (same ΔR).

NLOX PROOF OF CONCEPT: $Wb\bar{b}$

Preliminary [S. Honeywell, S. Quackenbush, L. Reina, CR, D. Wackeroth]

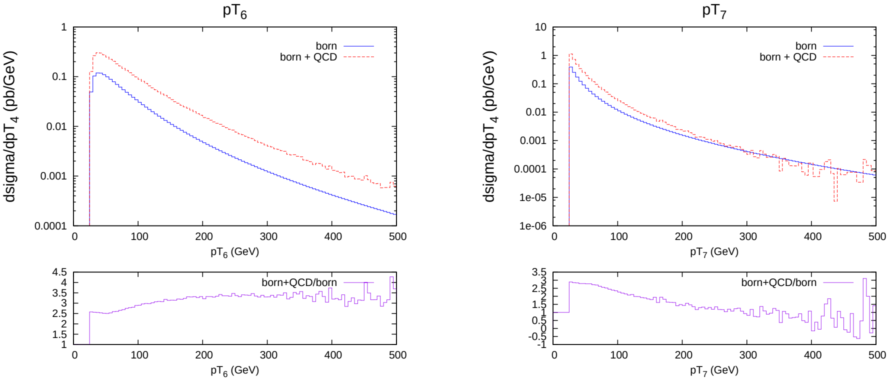




- $\alpha_s^2\alpha_e^1$ “Born” & $\alpha_s^3\alpha_e^1$ “QCD correction”
- $p_\perp$ of W^+(pT_3): 350% correction at 500 GeV
- η of W^+(rap_3): large corrections in $|\eta|$

NLOX PROOF OF CONCEPT: $Wb\bar{b}$

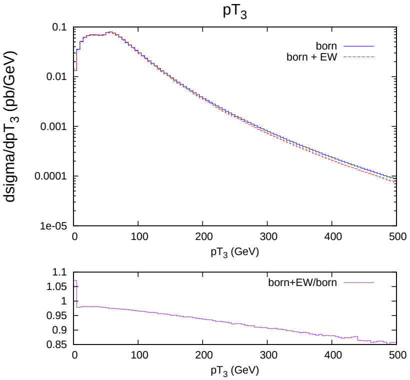
Preliminary [S. Honeywell, S. Quackenbush, L. Reina, CR, D. Wackeroth]

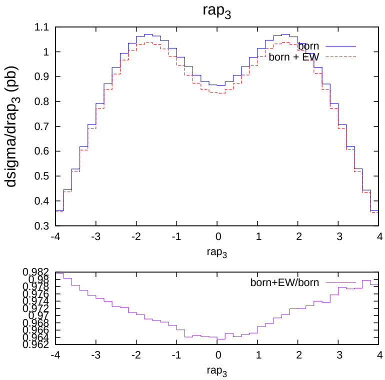


- $\alpha_s^2\alpha_e^1$ “Born” & $\alpha_s^3\alpha_e^1$ “QCD correction”
- $p_\perp$ of hardest (pT_6) and 2nd hardest (pT_7) b jet
- Corrections to hardest b-jet pT increasing
- Corrections to 2nd hardest b-jet pT decreasing

NLOX PROOF OF CONCEPT: $Wb\bar{b}$

Preliminary [S. Honeywell, S. Quackenbush, L. Reina, CR, D. Wackeroth]

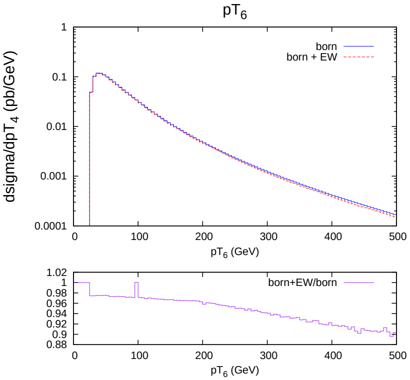


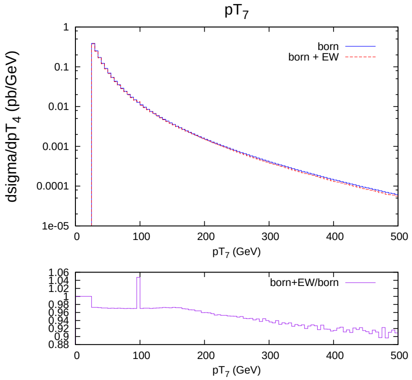


- $\alpha_s^2\alpha_e^1$ “Born” & $\alpha_s^2\alpha_e^2$ “EW correction”
- $p_\perp$ of W^+(pT_3): -15% correction at 500 GeV
- η of W^+(rap_3): small 2% changes in $|\eta|$

NLOX PROOF OF CONCEPT: $Wb\bar{b}$

Preliminary [S. Honeywell, S. Quackenbush, L. Reina, CR, D. Wackeroth]

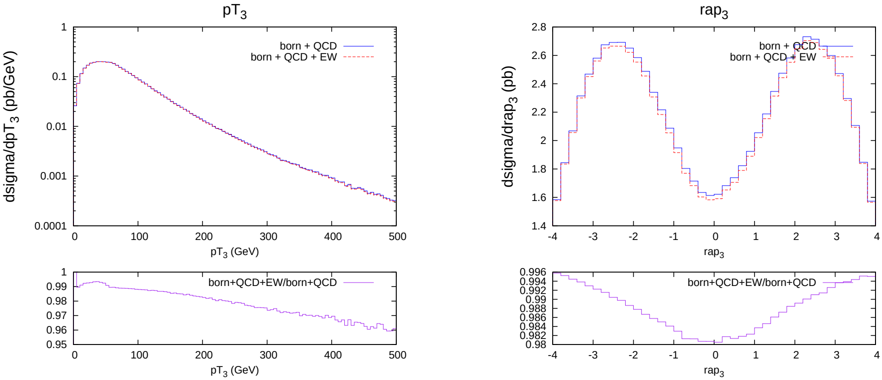




- $\alpha_s^2\alpha_e^1$ “Born” & $\alpha_s^2\alpha_e^2$ “EW correction”
- $p_\perp$ of hardest (pT_6) and 2nd hardest (pT_7) b jet
- Corrections to hardest b-jet: -10% at 500 GeV
- Corrections to 2nd hardest b-jet: -10% at 500 GeV (same as hardest b-jet)

NLOX PROOF OF CONCEPT: $Wb\bar{b}$

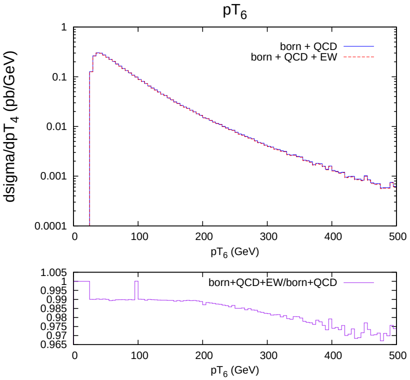
Preliminary [S. Honeywell, S. Quackenbush, L. Reina, CR, D. Wackeroth]

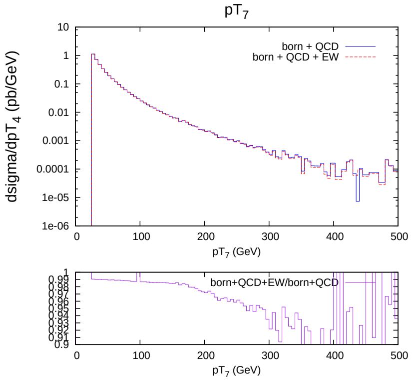


- $\alpha_s^2\alpha_e^2$ "EW correction" on top of $\alpha_s^2\alpha_e^1$ + $\alpha_s^3\alpha_e^1$ "Born +QCD NLO"
- "QCD correction" dominates, but still $p_\perp$ of W^+(pT_3): -4% correction at 500 GeV
- Also η of W^+(rap_3) still shows small 2% changes

NLOX PROOF OF CONCEPT: $Wb\bar{b}$

Preliminary [S. Honeywell, S. Quackenbush, L. Reina, CR, D. Wackeroth]





- $\alpha_s^2\alpha_e^2$ "EW correction" on top of $\alpha_s^2\alpha_e^1$ + $\alpha_s^3\alpha_e^1$ "Born +QCD NLO"
- "QCD correction" dominates, but still $p_\perp$ of hardest b-jet (pT_6): -3% correction at 500 GeV
- In the $p_\perp$ of 2nd hardest b-jet (pT_7): Even -10% drop recognizable

Checks:

- PSP check vs. Recola for all the virtual contributions. OK
- PSP check vs. in-house code for $u\bar{d} \to W^+ b\bar{b}$ virtual QCD. OK
- NLOX+Cuba sampling and integration checked for tree-level $u\bar{d} \to W^+ b\bar{b}(\gamma)$. OK
- NLOX+Cuba sampling and integration checked for $bg \to Zb$, EW and QCD corrections. OK
- NLOX+Cuba cross sections checked vs. using Recola MEs for all virtual contributions. OK
- In-house cross-reference checks of the real emission code for $W^+ b\bar{b}$. OK
- Run-time comparison for the ME evaluation of virtual contributions: $\mathcal{O}$(Recola)

Cross sections:

- $\sigma(\alpha_s^2 \alpha_e^1)_{\rm Born}$: (7.32176$\pm$0.00139) pb
- $\sigma(\alpha_s^2 \alpha_e^2)_{\rm virt}$: (-0.22769$\pm$0.0005) pb
- $\sigma(\alpha_s^3 \alpha_e^1)_{\rm virt}$: (-5.9828$\pm$0.0012) pb
- $\sigma(\alpha_s^2 \alpha_e^2)_{\rm real,\,soft/coll}$: (-0.51553$\pm$0.0002) pb
- $\sigma(\alpha_s^2 \alpha_e^2)_{\rm real,\,hard}$: (0.58208$\pm$0.00015) pb
- $\sigma(\alpha_s^3 \alpha_e^1)_{\rm real,\,soft/coll}$: (-52.36649$\pm$0.01) pb
- $\sigma(\alpha_s^3 \alpha_e^1)_{\rm real,\,hard}$: (70.97414$\pm$0.01) pb

- $\sigma(\alpha_s^2 \alpha_e^2)$:
  (0.16114$\pm$ $\sim$0.0002) pb
  -2% correction wrt Born
- $\sigma(\alpha_s^3 \alpha_e^1)$:
  (12.625$\pm$ $\sim$0.01) pb
  +172% correction wrt Born

- NLOX as automated tool for QCD and EW one-loop corrections
- One-loop EW and QCD computations in the SM (can be extended) for $2 \to 4$
- Proof of principle: $W^+ b\bar{b}$ EW+QCD corrections (only parts; full study will follow)

Work in progress

- Increase efficiency some more
- Finish the OLP interface and start testing with event generators
- Add to the reduction library
- Add to the accuracy checks
- Implement Complex-mass scheme
- Phenomenological studies and publication of code

In the long-run

- Automated PS slicing code to have an independent automatic framework
- Own implementation of dipole subtraction
- Organization in terms of color amplitudes
- Spin-helicity amplitudes
- ...

THANK YOU