Automation of EW and QCD one-loop corrections with NLOX

— status update —

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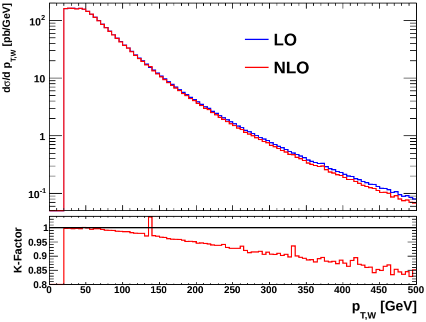
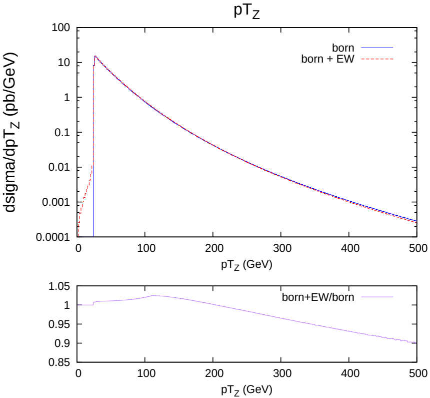
- VBs + jets important final states in searches for NP and Higgs precision studies.
- EW corrections important in high-energy tails of distributions, where also NP effects are expected.



- $p_\perp$ of the W in W+2 jets.
- -15% EW correction at 500GeV.
  [GoSam + MadDipole; plot from Chiesa, Greiner, Tramontano, arXiv:1507.08579]



- $p_\perp$ of the Z in $bg \to Zb$.
- -10% EW correction at 500GeV.
  [NLOX + inhouse PS slicing; plot from S. Honeywell, PhD thesis]

- 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 any SM process "at the push of a button".

- Paradigm shift:

  Dedicated ME providers (OLPs; one-loop providers) & event generators interface on the code level.

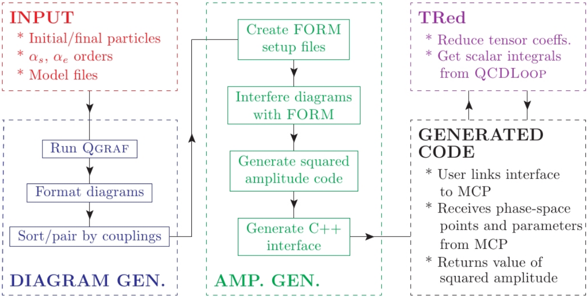
- This trend continues in the EW direction:

  Many OLPs have extended their range of applicability to the automation of EW corrections.

- Examples:
  - [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].

Currently developed by [S. Honeywell, S. Quackenbush, L. Reina, CR]

- NLOX (NLO X-Sections): Early version used for QCD corrections to $Wb\bar{b}$+jet [Reina, Schutzmeier, arXiv:1110.4438]
- Introduced as code for automated one-loop EW corrections last August (LoopFest XV). 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; Fully renormalized EW and QCD one-loop corrections; User friendly interface; Flexible 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 custom C++ tensor reduction library TRED



NLOX has come a long way during the past 2 years:

- Color-and helicity-summed tree-level and one-loop matrix elements in the SM (up to $2 \to 4$).
  - At the moment we have two models, one with only the top massive and one with bottom and top massive.
- UV and IR regularized using dimensional regularization.
  - AG5 (fully anti-commuting γ_5 scheme, modified CDR with non-loop objects in 4D).
  - HV scheme also implemented (only 4D γ_μ's anti-commute with γ_5), but the EW CTs need modification.
- 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.
  - Minimal specifications: Process, born and virtual coupling powers on the squared amplitude level, tree and loop coupling powers on the amplitude level.
  - Parameters are provided through parameter files, or on the level of generated C++ code.
- 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 generator (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]

- 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
  - Vertex and prop. counterterms for QCD and EW corrections in terms of renormalization constants.
  - From them build UV counterterm diagrams (QGraf, Python).
  - Consistent treatment of mass counterterm insertion, etc.
- Amplitude level
  - Simplify color structures, and collect same ones (Form).
  - Perform Lorentz decomposition in case of loop diagrams (Form).
  - Simplify Dirac structures as much as possible (Form).
  - Collect terms belonging to the same Dirac string (standard-matrix-element; SME) (Form).
- Squared amplitude level
  - Produce all pairings of diagrams, collect those with the same coupling power (Python; actually happens already before amplitude stage).
  - Multiply collected color structures and evaluate (Form).
  - Multiply SMEs and simplify resulting structures as much as possible (Form).
  - Collect unique structures on the squared SME level (Form, Python).
  - Generate C++ code in terms of squared SMEs, suitable for TRed (Python).

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

- The Lorentz decomposition to tensor coefficients is done on the diagram level in the Form code.
- In the C++ code generation phase the list of tensor coefficients needed for the process is accumulated.
- At code execution the list of tensor coefficients is sent to TRed.
- As each tensor coefficient is added also a tree of dependencies is added, as pointers to tensor coefficients that are already in the list, down to needed scalar integrals.
- For each PSP TRed computes and caches a set of needed invariants, then computes each tensor coefficient.

⇒ Building up a tree of possible scalar coefficients, compute their values (QCDLoop [Ellis, Zanderighi]) as they are encountered and cache for reuse.

- Passarino-Veltman reduction [Passarino, Veltman, 1979] for 4-pt and lower
- Denner-Dittmaier reduction [Denner, Dittmaier, 2005] for 5-pt and higher

Taken from [S. Honeywell, PhD thesis].

$$u\bar{u} \to g d\bar{d}$$

	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

$$d\bar{d} \to ggg$$

	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

$$gg \to \gamma t\bar{t}$$

	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

$$gg \to Zt\bar{t}$$

	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

Taken from [S. Honeywell, PhD thesis].

$$gg \to ht\bar{t}$$

	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

$$u\bar{u} \to ht\bar{t}$$

	Order	NLOX	Recola
Born	$\mathcal{O}(\alpha_s^2 \alpha_e)$	0.0002461124726272914	0.2461124726272914E-03
C_2/Born	$\mathcal{O}(\alpha_s^3 \alpha_e)$	-2.66666666665627	-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

$$u\bar{u} \to d\bar{d}c\bar{c}$$

	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

$$u\bar{u} \to b\bar{b}t\bar{t}$$

	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

Taken from [S. Honeywell, PhD thesis].

$$gg \to b\bar{b}t\bar{t}$$

	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

$$u\bar{d} \to e^+\nu_e b\bar{b}$$

	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].

$bg \to Zb$, with massive b-quarks

	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

$$e^+ e^- \to \mu^+ \mu^-$$

	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

$$e^+ \nu_e \to \mu^+ \nu_\mu$$

	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

$$\nu_e \bar{\nu}_e \to \nu_\mu \bar{\nu}_\mu$$

	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

Taken from [S. Honeywell, PhD thesis].

$$\nu_e \bar{\nu}_e \to ZZ$$

	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

$$e^- \gamma \to e^- \gamma$$

	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

$$ug \to \gamma u$$

	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

$$e^- \gamma \to e^- \gamma \gamma$$

	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

Taken from [S. Honeywell, PhD thesis].

$$\nu_e \bar{\nu}_e \to Z \nu_\mu \bar{\nu}_\mu$$

	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

$$\nu_e \bar{\nu}_e \to \nu_\mu \bar{\nu}_\mu \nu_\tau \bar{\nu}_\tau$$

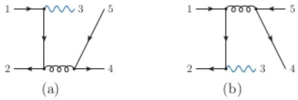
	Order	NLOX	Recola
Born	$\mathcal{O}(\alpha_e^4)$	3.551592719063201e-08	0.3551592719063195E-07
C_2/Born	$\mathcal{O}(\alpha_e^5)$	0	0
C_1/Born	$\mathcal{O}(\alpha_e^5)$	-17.7777777777776	-17.77777777777923
C_0/Born	$\mathcal{O}(\alpha_e^5)$	-231.0050069559277	-231.0050069682861

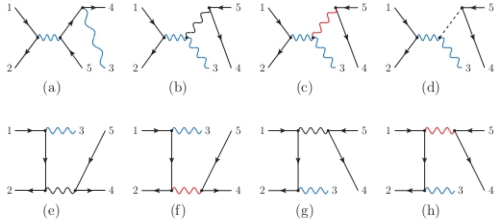
$Wb\bar{b}$ FOR PROOF OF CONCEPT

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

- No clear notion of “EW corrections” or “QCD corrections” to a certain Born.
- Need to include all possible coupling-power combinations to a certain process.

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





- Lowest orders:

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

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

  all zero due to color

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

  not considered due to α_e^3 suppression

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

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

One-loop amplitude level

g^0e^5 (no virtual gluons)	g^4e1 (no virtual EW VBs)	g^2e^3 (mixed)
1084 diagrams	37 diagrams	193 diagrams

Interference level

$\alpha_s^0\alpha_e^4 = g^0e^3$ tree $\times g^0e^5$ loop pure EW virtual; 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

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

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

g or γ radiation, diagram level, e.g

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

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

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

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

interference 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

g or γ in. state, diagram level, e.g

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

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

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

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

interference 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

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 of contribution $g^2e^1 \times g^0e^3 + cc$
  They are not zero, but small, so we drop them (also the corres. hard real, which is also small)
  $\Rightarrow$ real $\alpha_s^2\alpha_e^2$ only from γ-emission & real j-emission (glues / light quarks) only contributes at $\alpha_s^3\alpha_e^1$

```
mb = 4.75;    mt = 173;
mW = 80.385;  mZ = 91.1876;
mH = 125;     mu = mW+2.*mb;
// alpha_s(mu=mW+2.*mb=89.885) of CT14
alpha_s = 0.11825723468285827;
g = sqrt(4.*PI*alpha_s);
// alpha_e(0) = 0.0072973525698163l5
alpha_e = 1./137.035999074;
e = sqrt(4.*PI*alpha_e);
```

- $\alpha(0)$ EW input scheme
- 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,\mathrm{min}}^{b/\bar{b}} = $25 GeV and $|\eta^{b/\bar{b}}|_{\mathrm{max}} = $2.5.
- Simple separation cut of b and $\bar{b}$ with $\Delta R_{\mathrm{min}} = $0.4.
- Simple recombination of j's and γ's with b's; same ΔR_{min}.

- In our contributions: interferences with massive VB propagators, e.g. in g^2e^1 tree $\times$ g^2e^3 loop.
- Singular when massive VB propagator momentum turns on-shell.
- These pop up in only one diagrammatic side of the interferences, e.g. in g^2e^3 loop but not g^2e^1 tree $\Rightarrow$ there are no physical resonances, but the integrator still has to integrate over singular regions.

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

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

- Why? No complex-mass (CM) scheme yet.
  Used zero widths for now.

- In the literature, for on-shell W the question is:
  - * W^* with CM connected to on-shell W without CM (via γ-radiation or -exchange) $\rightarrow$ soft sing. turn into logs of widths.
  - * Polarization sums: What to use for M_W for an on-shell W in CM scheme?
  - * Literature: In the CM scheme "the on-shell prescription should be abandoned".

- Various approaches to regulate pseudo-resonant Z, H and t if not using CM scheme:
  - Cut on events with large K-factor [GoSam (+MadDipole), Chiesa, Greiner, Tramontano, arXiv:1507.08579]
  - Implement technical width in critical propagators [OpenLoops (+Sherpa,+Munich), Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr, arXiv:1412.5157]
  - We cut on inv. masses in all contributions: no gauge inv. violation, but restricts phase space.

- So:
  - With CMs regulating soft singularities, one should not worry about soft $W^* \rightarrow W\gamma$: soft sing. turn into logs of widths; they will pop up also in virt and one accepts them. Simple in PS slicing: leave out soft eikonal for $W^* \rightarrow W\gamma$. How about in a subtraction scheme?
  - What about other issues if wanting to use CM, like gauge inv. violation due to polarizations of on-shell Ws? Is the only way to always run (computationally expensive) fully off-shell?

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

Checks:

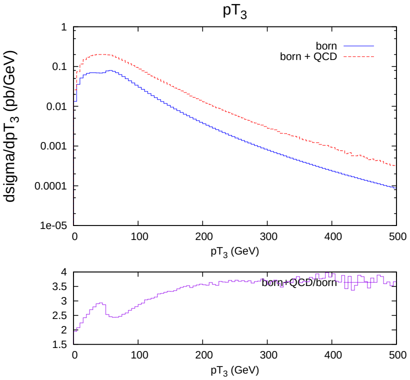
- PSP check vs. Recola for all the virtual contributions. OK
- PSP check vs. in-house code for $u\bar{d} \to W^+ b\bar{b}$ virtual QCD. OK
- NLOX+Cuba sampling and integration checked for tree-level $u\bar{d} \to W^+ b\bar{b}(\gamma)$. OK
- NLOX+Cuba sampling and integration checked for $bg \to Zb$, 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 the virtual contributions: $\mathcal{O}$(Recola)

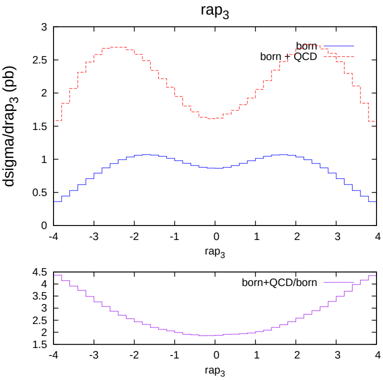
Cross sections:

- $\sigma(\alpha_s^2 \alpha_e^1)$:
  (7.32176$\pm$0.00139) pb
- $\sigma(\alpha_s^3 \alpha_e^1)$:
  (12.625$\pm$ $\sim$0.01) pb
  +172% correction wrt $\alpha_s^2 \alpha_e^1$
- $\sigma(\alpha_s^2 \alpha_e^2)$:
  (0.16114$\pm$ $\sim$0.0002) pb
  -2% correction wrt $\alpha_s^2 \alpha_e^1$

- $\sigma(\alpha_s^3 \alpha_e^1)_{\rm virt}$: (-5.9828$\pm$0.0012) 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
- $\sigma(\alpha_s^2 \alpha_e^2)_{\rm virt}$: (-0.22769$\pm$0.0005) 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

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

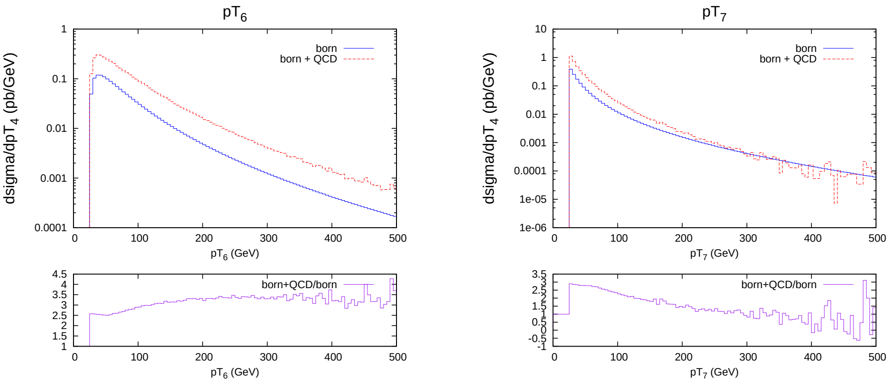




- $\alpha_s^2\alpha_e^1$ “Born” & $\alpha_s^3\alpha_e^1$ “QCD correction”
- $p_\perp$ of W^+(pT_3): 350% correction at 500 GeV
- η of W^+(rap_3): large corrections in $|\eta|$

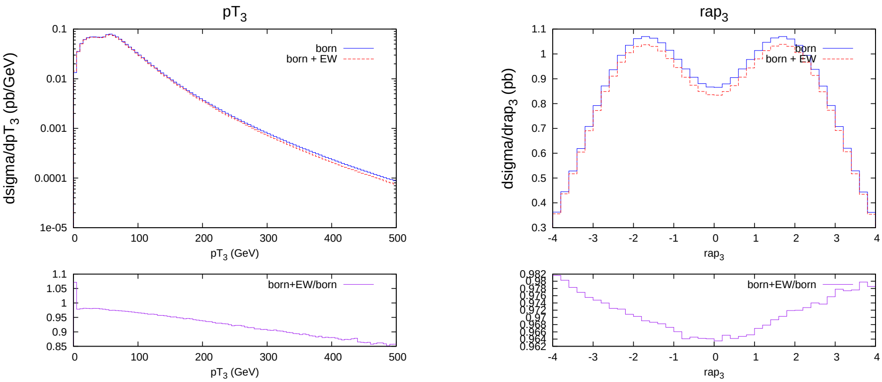
$Wb\bar{b}$ FOR PROOF OF CONCEPT

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



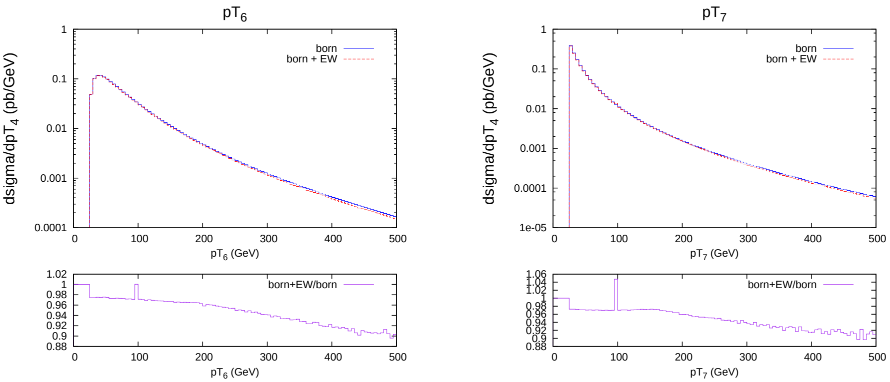
- $\alpha_s^2\alpha_e^1$ “Born” & $\alpha_s^3\alpha_e^1$ “QCD correction”
- $p_\perp$ of hardest (pT_6) and 2nd hardest (pT_7) b jet
- Corrections to hardest b-jet $p_\perp$ increasing
- Corrections to 2nd hardest b-jet $p_\perp$ decreasing

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



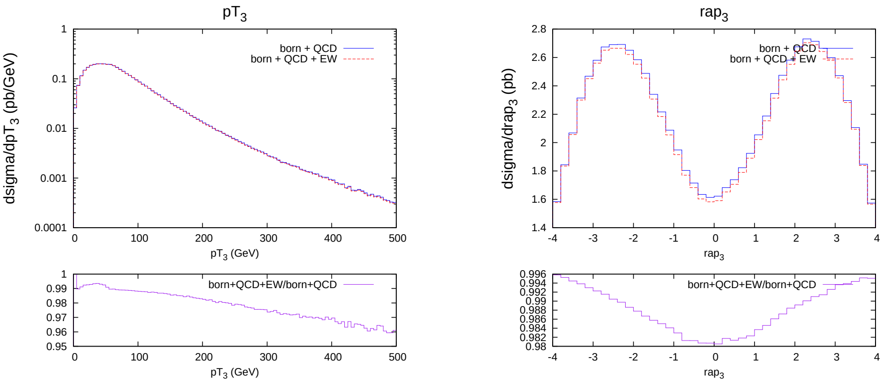
- $\alpha_s^2\alpha_e^1$ “Born” & $\alpha_s^2\alpha_e^2$ “EW correction”
- $p_\perp$ of W^+(pT_3): -15% correction at 500 GeV
- η of W^+(rap_3): small 2% changes in $|\eta|$

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 $p_\perp$: -10% at 500 GeV
- Corrections to 2nd hardest b-jet $p_\perp$: -10% at 500 GeV

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



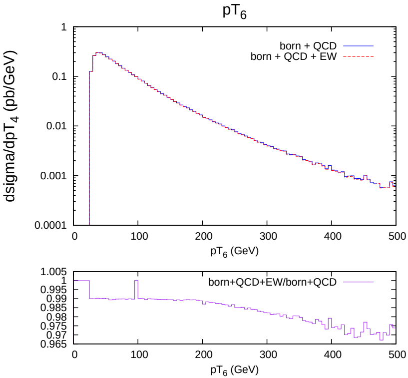
- $\alpha_s^2\alpha_e^2$ “EW correction” on top of $\alpha_s^2\alpha_e^1$ “Born” + $\alpha_s^3\alpha_e^1$ “QCD correction”
- “QCD correction” dominates. Still, $p_\perp$ of W^+(pT_3): -4% correction at 500 GeV
- Also η of W^+(rap_3) still shows small 2% changes

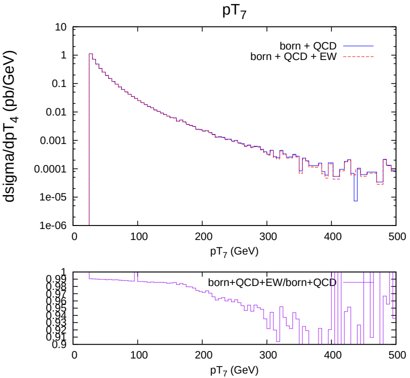
Going exclusive: Requiring exactly 2 jets should enhance the “EW corrections” wrt the “QCD corrections”.

Going inclusive: Adding γ-induced and heavy VB radiation would diminish the effects of the “EW corrs.”?

$Wb\bar{b}$ FOR PROOF OF CONCEPT

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





- $\alpha_s^2\alpha_e^2$ “EW correction” on top of $\alpha_s^2\alpha_e^1$ “Born” + $\alpha_s^3\alpha_e^1$ “QCD correction”
- “QCD correction” dominates. Still, $p_\perp$ of hardest b-jet (pT_6): -3% correction at 500 GeV
- $p_\perp$ of 2nd hardest b-jet (pT_7): Even -10% drop recognizable (more statistics needed)

Going exclusive: Requiring exactly 2 jets should enhance the “EW corrections” wrt the “QCD corrections”.

Going inclusive: Adding γ-induced and heavy VB radiation would diminish the effects of the “EW corrs.”?

NLOX

- Automated QCD & EW one-loop corrections (up to $2 \to 4$ in the SM)
- Proof of principle: $W^+ b\bar{b}$ EW+QCD corrections (only parts; full study will follow)

Work in progress

- Increase efficiency some more
- Finish OLP interface; test with event generators
- Extend the reduction library
- Add accuracy checks
- Implement complex-mass scheme
- Phenomenological studies and publication of code

In the long-run

- Automate PS slicing, for fully integrated QCD & EW NLO framework
- On the other hand: implement dipole subtraction
- Organization in terms of color amplitudes
- Spin-helicity amplitudes
- ...

Open questions on my side

- EW input (only $\alpha_e(0)$, mixed scheme with $\alpha_e(G_\mu)$ and $\alpha_e(0)$, ...)?
- On-shell W production and CM scheme?
- Including / not including γ-initiated or W/Z-radiation?

THANK YOU