Electroweak top-quark pair hadroproduction in the presence of Z' bosons in POWHEG

I. Schienbein
Univ. Grenoble Alpes/LPSC Grenoble

based on:
R. Bonciani, T. Jezo, M. Klasen, D. Lamprea, F. Lyonnet, I. Schienbein,

Outline
Introduction
The calculation
Numerical results
Conclusions

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Introduction
Motivation pour $Z' \rightarrow t + \overline{t}$

- New heavy resonances $Z'$ are predicted in a variety of models with extra $U(1)$ or $SU(2)$ symmetry, e.g.,
  - $E_6 \rightarrow SO(10) \times U(1)_\psi$, $SO(10) \rightarrow SU(5) \times U(1)_\chi$
  - LR symmetric models: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_Y$
  - $G(221)$ models: $SU(3)_c \times SU(2)_1 \times SU(2)_2 \times U(1)_X$
- In many cases, the $Z'$ can decay leptonically and the strongest constraints come from searches with leptonic final states [JHEP12(2014)092]
- Nevertheless, final states with top quarks are very interesting:
  - The heavy top quark may play a special role w.r.t. to EWSB and BSM physics which couples preferentially to the third generation or not to leptons
  - Even for models with couplings to leptons, the addition of top quark observables is important to distinguish between different BSM scenarios [PRD86(2012)035005]
Here, we present our new calculation of NLO QCD corrections to EW top-pair production at the LHC in the presence of a $Z'$ boson [arXiv:1511.08185]

- $Z'$ boson with general (flavour diagonal) couplings to SM fermions
- Results are implemented in the POWHEG BOX MC event generator
- Standard Model and new physics interference effects taken into account
- QED singularities consistently subtracted
- Numerical results for the Sequential SM and a leptophobic TopColor model
- SM and $Z'$ total cross sections
- Distributions: invariant mass, transverse momentum, azimuthal angle, rapidity of the top-quark pair
Leptophobic topcolor model

- **New strong dynamics** with $SU(3)_2$ symmetry coupling preferentially to the third generation while the original $SU(3)_1$ gauge group couples only to the 1st and 2nd generation; breaking $SU(3)_1 \times SU(2)_2 \rightarrow SU(3)_c$

- Formation of top quark condensate generates large top mass

- To block the formation of a bottom quark condensate an additional $U(1)_2$ symmetry with associated $Z'$ is introduced; $U(1)_1 \times U(1)_2 \rightarrow U(1)_Y$

- Different couplings of the $Z'$ to the three fermion generations define different variants of the model

- **Leptophobic TC model**: (model IV in hep-ph/9911288)
  - $Z'$ couples only to 1st and 3rd generation
  - no significant coupling to leptons
  - experimentally accessible cross section at the LHC
Leptophobic topcolor model

- **Three parameters** (in addition to $M_{Z'}$):
  - Ratio of the two $U(1)$ coupling constants: $\cot \Theta_H$
  - $f_1$: relative strength of the $Z'$-coupling to right-handed up-type quarks w.r.t. to the left-handed up-type quarks
  - $f_2$: same for down-type quarks

- $\cot \Theta_H$ should be large to enhance the condensation of top quarks but no bottom quarks

- The **LO cross sections** are usually computed using
  - a fixed small $Z'$ width (which fixes $\cot \Theta_H$): $\Gamma_{Z'} = 1.2\% M_{Z'}$
  - $f_1=1, f_2=0$ (maximes the fraction of $Z'$ bosons decaying into top pairs)
The calculation
Top-quark pair production

The partonic top-quark pair production cross section at NLO:

$$\sigma_{ab}(\mu_r) = \sigma_{2;0}(\alpha_S^2) + \sigma_{0;2}(\alpha^2) + \sigma_{3;0}(\alpha_S^3) + \sigma_{2;1}(\alpha_S^2 \alpha) + \sigma_{1;2}(\alpha_S \alpha^2) + \sigma_{0;3}(\alpha^3)$$

- $\sigma_{2;0}$: SM QCD background
- $\sigma_{3;0}$: NLO QCD corrections to the SM background

- NLO known since the late 80ths
  - Nason, Dawson, Ellis '88/'89
  - Beenakker, Kuif, van Neerven, Smith '89
  - Bojak, Stratmann '03: polarized case

- NLO predictions for heavy quark correlations
  - Mangano, Nason, Ridolfi '92

- Spin correlations between t and tbar
  - Bernreuther, Brandenburg, Si, Uwer, '01/'04

- NNLO calculation recently completed
  - Czakon, Mitov '13: $\sigma_{tot}$
  - Czakon, Mitov '14: distributions
The partonic top-quark pair production cross section at NLO:

\[
\sigma_{ab}(\mu_r) = \sigma_{2;0}(\alpha_S^2) + \sigma_{0;2}(\alpha^2) + \sigma_{3;0}(\alpha_S^3) + \sigma_{2;1}(\alpha_S^2\alpha) + \sigma_{1;2}(\alpha_S\alpha^2) + \sigma_{0;3}(\alpha^3)
\]

- **\(\sigma_{2;0} \):** SM QCD background
- **\(\sigma_{3;0} \):** NLO QCD corrections to the SM background
- **\(\sigma_{2;1} \):** EW corrections to the QCD background

- **Gauge invariant subset, no QCDxEW interferences from box diagrams**
  - Beenakker, Denner, Hollik, Mertig, Sack, Wackeroth ’94
  - Kao, Wackeroth ’00: 2HDM

- **Rest of EW corrections including Z-gluon interferences and corrections from real and virtual photons**
  - Kühn, Scharf, Uwer, ’06
  - Moretti, Nolten, Ross ’06
  - Bernreuther, Fuecker, Si ’06
  - Hollik, Kollar ’08
The partonic top-quark pair production cross section at NLO:

\[ \sigma_{ab}(\mu_r) = \sigma_{2;0}(\alpha_S^2) + \sigma_{0;2}(\alpha^2) + \sigma_{3;0}(\alpha_S^3) + \sigma_{2;1}(\alpha_S^2\alpha) + \sigma_{1;2}(\alpha_S\alpha^2) + \sigma_{0;3}(\alpha^3) \]

**Existing calculations including a Z’ boson:**

- Factorized approach (no SMxZ’, no qg-channel with Z’), purely vector or axial vector or left or right couplings  
  Gao, C.S. Li, B.H. Li, Yuan, Zhu ’10

- no SMxZ’, includes: qg-channel, top-decay in NWA with spin correlations, Z’ contribution to \( \sigma_{2;1} \) (broad resonances)  
  Caola, Melnikov, Schulze ’13

**Our calculation:** includes: SMxZ’ interferences, general couplings, QED contribution, POWHEG implementation, no top-decay, no Z’ contribution to \( \sigma_{2;1} \)

- \( \sigma_{0;2} \): EW top-quark pair production  

- \( \sigma_{1;2} \): NLO QCD corrections to EW top-quark pair production

- \( \sigma_{0;3} \): negligible
LO subprocesses: $\sigma_{2;0}$ and $\sigma_{0;2}$

- $\hat{\sigma}^{\text{LO}} = \hat{\sigma}^{\text{LO}}_S(\alpha^2_S) + \hat{\sigma}^{\text{LO}}_W(\alpha^2_W)$

- **SM**
  - $gg, \mathcal{O}(\alpha^2_S)$:
  - $q\bar{q}, \mathcal{O}(\alpha^2_S)$:
  - $q\bar{q}, \mathcal{O}(\alpha^2_W)$:

- **beyond SM**
  - $q\bar{q}, \mathcal{O}(\alpha^2_W)$:
LO

\[ \hat{\sigma}^{\text{NLO}} = \hat{\sigma}(\alpha_S^2) + \hat{\sigma}(\alpha_W^2) + \hat{\sigma}(\alpha_S^3) + \hat{\sigma}(\alpha_S^2 \alpha_W) + \hat{\sigma}(\alpha_S \alpha_W^2) + \hat{\sigma}(\alpha_W^3) \]

- \( \mathcal{O}(\alpha_S^3) \) not affected by the presence of \( Z' \)
- we calculate \( \mathcal{O}(\alpha_S \alpha_W^2) \)
interferences of real and real diagrams
new channel as compared to tree-level and 1-loop diagrams
no loops, no UV divergences
IR divergences, after integration over 1 particle phase space
  - soft (S) divergences: radiation of a soft gluon (a), (b)
  - initial state collinear (ISC) divergences: (b), (d)
  - no final state collinear (FSC) divergences
• The $gq$-channel has an initial state C-div. associated to a photon propagator

• For the mass factorization procedure need to introduce a photon PDF and have to include photon-initiated subprocesses

• Counting the photon PDF as $\mathcal{O}(\alpha)$ the LO $g\gamma$-channel contributes to $\sigma_{1;2}(\alpha_s\alpha^2)$

• This channel turns out to be numerically important
Shower Monte Carlo’s (SMCs) at NLO QCD

• SMCs@LO
  ➢ automatically generate low angle radiation via PS
  ➢ simulates hadronization, decay of unstable hadrons
  ➢ resums contributions in near collinear regions to all orders
  ➢ lack accuracy

• SMCs@NLO: non-trivial
  ➢ PS generates higher-order contributions in collinear regions
  ➢ NLO QCD already contains those contributions
  ➢ application of PS on NLO QCD would lead to overcounting

• PS and NLO QCD calculation need to be matched
  ➢ MC@NLO: SMC dependent, can lead to events with negative weights
  ➢ POWHEG: SMC independent, only positive weighted events

MC@NLO: hep-ph/0305252 ; POWHEG: arXiv:0707.3088
POWHEG Box implementation

User input:

- List of all flavour structures of tree level (Born, Real) processes
- Born phase space
- Born amplitude squared, Color-correlated Born amplitude, Spin-correlated Born amplitude
- Finite part of the virtual amplitude
- Real amplitude squared

POWHEG Box:

- Finds all the singular regions
- Constructs the soft and collinear counter terms
- Builds the collinear remnants (i.e. the finite part after the subtractions)
- Generates the events with Born kinematics (including the virtual corrections)
- Generates the hardest emission of the PS

POWHEG Box implementation

**QED contribution:**

- The diagrams above involve photon-initiated underlying Born diagrams, preceded by a splitting of a quark into a photon.
- The corresponding QED singularities were so far not treated properly in POWHEG (only the singular emission of final state photons had been implemented in version 2 of POWHEG BOX).

We therefore

- replaced the POWHEG subtraction for the $q \to g + q$ splitting by a similar procedure for the QED $q \to \gamma + q$ splitting.
- enabled the POWHEG flag for real photon emission (which then allows for the automatic factorization of the QED singularity and the use of photon PDFs).
- implemented the photon-initiated Born structures.
Validation

- Our implementation of EW top pair production with Z’ contributions has been added to the list of POWHEG processes under the name: \textit{PBZp}

- Our SM Born, Real amplitudes in agreement with \textit{MadGraph5_aMC@NLO}

- $1/\epsilon$ expansion of our virtual matrix elements checked against \textit{GoSam}

- For the full calculation: UV and IR divergences cancel

- Checked completeness relations for color- and spin-correlated Born amplitudes

- Did the automated \textit{POWHEG} checks for the kinematic limits of the real emission amplitudes

- For the q-qbar process in the SM: total hadronic cross section in agreement with \textit{MadGraph5_aMC@NLO} (which does not allow for a proper treatment of the QED divergence in the gq subprocess)

- Agreement with \textit{Gao et al} within 2% if we reduce our calculation to their setup [no SMxZ’, no gq-channel, purely vector or purely axial-vector couplings]

- Agreement with the K-factors of \textit{Caola et al} if we remove the SMxZ’ interferences and the factorizable QCD corrections to the top quark decay

Tuesday 24 May 16
Numerical results
Numerical results: Input

- With our **POWHEG** implementation **PBZp** at LO and NLO coupled to the PS and hadronization procedure in **PYTHIA 8**

- Results for LHC13 (total cross sections also at LHC14)

- **NNPDF23_nlo_as0118_qed** PDFs (including a photon PDF)

- central scale choice: $\mu_R^2 = \mu_F^2 = \text{shat}$
  (applies also to the SM channels where no $M_{Z'}$ present)

- Models:
  - **SSM**: $\Gamma/M_{Z'} = 3.2\%$
  - **leptophobic TopColor (LPTC)**: $\Gamma/M_{Z'} = 1.2\%$, $f_1=1$, $f_2=0$
Resonant-only $Z'$-boson production at NLO

- **SSM (lower curves):**
  - For $L_{int} = 100 \text{ fb}^{-1}$, LHC13: number of expected events $10^4 (M_{Z'}=2 \text{ TeV}) ... 10 (M_{Z'}=6 \text{ TeV})$
  - Uncertainties range from 15% - 35%
  - Interestingly, the PDF uncertainty dominates over entire $M_{Z'}$ range shown

- **LPTC model:** Uncertainties range from 15% - 20%. Scale uncertainty dominates for $M_{Z'} < 5 \text{ TeV}
The K-factor ranges from 1.3 to 1.45.

Not entirely mass-independent even for resonant only Z’-boson production!
Steeply falling spectra from $10^{-2}$ to $10^{-7}$ pb/GeV

TC resonance peak about an order of magnitude larger (for the chosen couplings)

K-factors highly dependent on invariant mass region (position of resonance peak shifted to lower masses at NLO compared to LO due to radiation)

Red dashed line: ratio of result obtained with PYTHIA over HERWIG as parton shower
Effect of interferences

- Blue curves: without interference terms
- Green curves: with interference terms
  Shifts resonance peak to smaller masses

- Ratio = Blue curve/Green curve
  Predictions without interferences overestimate the true signal by a factor of >2
Charge asymmetry $A_c$

\[
A_c = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)}
\]

\[
\Delta |y| = |y_t| - |y_{\bar{t}}|
\]

- Charge asymmetry known to be quite sensitive to distinguish different models
- At the resonance: $A_c = 11 \pm 1\%$ (SSM) vs $\pm 0.1\%$ (TC)
- Far below resonance: $A_c = 2.5 \pm 0.5\%$ (SSM and TC)
Conclusions
Conclusions

- Presented a new calculation of NLO QCD corrections to EW top-pair production at the LHC in the presence of a $Z'$ boson

- $Z'$ boson with general (flavour diagonal) couplings to SM fermions

- Results implemented in the POWHEG BOX MC event generator; called PBZp

- Standard Model and new physics interference effects taken into account. They are non-negligible in particular for the invariant mass distribution.

- QED singularities consistently subtracted. This contribution has a large impact.

- Showed numerical results for the Sequential SM and a leptophobic TopColor model

- SM and $Z'$ total cross sections

- Distributions: invariant mass, transverse momentum, azimuthal angle, rapidity of the top-quark pair

- Charge asymmetry promising to distinguish between models

- Similar calculation for the $W' \rightarrow tb$ case hopefully soon completed
Backup slides
Total cross sections for $M_{Z'} = 3$ TeV

For LO uses the NNPDF23_lo_as0119_qed PDF set

<table>
<thead>
<tr>
<th>Order</th>
<th>Processes</th>
<th>Model</th>
<th>$\sigma$ [pb]</th>
<th>$\sigma$ [pb] ($m_{tt} &gt; \frac{3}{4}m_{Z'}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO</td>
<td>$q\bar{q}/gg \to t\bar{t}$</td>
<td>pure QCD</td>
<td>473.93(7)</td>
<td>0.15202(2)</td>
</tr>
<tr>
<td>NLO</td>
<td>$q\bar{q}/gg + qg \to t\bar{t} + q$</td>
<td>photon ind. factor 1/100</td>
<td>1261.0(2)</td>
<td>0.45255(7)</td>
</tr>
<tr>
<td>LO</td>
<td>$\gamma g + g\gamma \to t\bar{t}$</td>
<td>pure EW factor 1/1000</td>
<td>4.8701(8)</td>
<td>0.004972(6)</td>
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<tr>
<td>LO</td>
<td>$\gamma g + g\gamma \to t\bar{t}$ (NLO $\alpha_s$ and PDFs)</td>
<td></td>
<td>5.1891(8)</td>
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<td>LO</td>
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<td>0.36620(7)</td>
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<td>LO</td>
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Total cross sections for $M_{Z'} = 3$ TeV

For LO uses the NNPDF23_lo_as0119_qed PDF set

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Table 1. Total cross sections in LO for top-pair production at $O(\alpha^2)$, $O(\alpha_s \alpha)$ and $O(\alpha^2)$ in the SM, SSM and TC, together with the corresponding NLO corrections. The $Z'$-boson mass is set to 3 TeV.
Total cross sections for $M_{Z'} = 3$ TeV

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<td>SSM</td>
<td>0.5676(1)</td>
<td>0.0051553(3)</td>
</tr>
<tr>
<td>NLO</td>
<td>$q\bar{q} + qg \to \gamma/Z'/Z' + q \to t\bar{t} + q$</td>
<td>SSM</td>
<td>4.172(2)</td>
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</tr>
<tr>
<td>LO</td>
<td>$q\bar{q} \to Z' \to t\bar{t}$</td>
<td>TC</td>
<td>0.012175(2)</td>
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<td>LO</td>
<td>$q\bar{q} \to \gamma/Z'/Z \to t\bar{t}$</td>
<td>TC</td>
<td>0.38647(7)</td>
<td>0.011984(2)</td>
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<tr>
<td>NLO</td>
<td>$q\bar{q} \to \gamma/Z'/Z' \to t\bar{t}$</td>
<td>TC</td>
<td>0.6081(2)</td>
<td>0.01468(1)</td>
</tr>
<tr>
<td>NLO</td>
<td>$q\bar{q} + qg \to \gamma/Z'/Z' + q \to t\bar{t} + q$</td>
<td>TC</td>
<td>4.202(2)</td>
<td>0.01002(1)</td>
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Total cross sections for $M_{Z'} = 3$ TeV

For LO uses the NNPDF23_lo_as0119_qed PDF set

<table>
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<tr>
<th>Order</th>
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<th>$\sigma$ [pb]</th>
<th>$\sigma$ [pb] $(m_{t\bar{t}} &gt; \frac{3}{4}m_{Z'})$</th>
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<tr>
<td>LO $q\bar{q} \rightarrow \gamma/Z \rightarrow t\bar{t}$</td>
<td>SM</td>
<td>0.36620(7)</td>
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</tr>
<tr>
<td>LO $\gamma + g \rightarrow t\bar{t}$</td>
<td>SM</td>
<td>0.5794(1)</td>
<td>0.00017174(1)</td>
<td></td>
</tr>
<tr>
<td>LO $\gamma + g \rightarrow t\bar{t}$ (NLO $\alpha_s$ and PDFs)</td>
<td>SM</td>
<td>4.176(2)</td>
<td>0.001250(2)</td>
<td></td>
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<tr>
<td>LO $q\bar{q} + gg \rightarrow \gamma/Z \rightarrow t\bar{t}$</td>
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<td>0.0050385(8)</td>
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Note: The NLO corrections for the purely electroweak processes are new even in the SM, where we have introduced a proper subtraction procedure for the photon-induced processes. The $K$-factors for the $q\bar{q}$ channel are moderate in the SM (+56%), SSM (+58%) and TC (+56%), where the last two numbers are dominated by SM contributions and therefore very similar. Only after the invariant-mass cut the differences in the models become more apparent in the $K$-factors for the SM ($\pm 0\%$), SSM (+19%) and TC (+23%). However, similarly to the QCD case the $qg$ channel, and also the $\gamma g$ channel opening up for the first time at this order, introduce contributions much larger than the underlying Drell-Yan type Born process. Note that the LO $\gamma g$ cross section computed with NLO $\alpha_s$ and PDFs must still be added to the full NLO $q\bar{q} + gg$ cross sections. An invariant-mass cut is then very instrumental to bring down the $K$-factors and enhance perturbative stability, as one can see from the LO $\gamma g$ and in particular the NLO results in the SSM and TC.
## Total cross sections for $M_{Z'} = 3$ TeV

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<td>473.93(7)</td>
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<td>NLO</td>
<td>$q\bar{q}/gg + qg \rightarrow t\bar{t} + q$</td>
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<td>1261.0(2)</td>
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<td>LO</td>
<td>$\gamma g + g\gamma \rightarrow t\bar{t}$</td>
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<td>4.8701(8)</td>
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Transverse momentum distributions particularly sensitive to soft parton radiation and the associated resummation in NLO+PS MCs

- Fixed NLO calculations (green) diverge at small transverse momentum.

- Physical turnover only at NLO+PS (red) or LO+PS (blue) level

- Red dashed line: result obtained with the HERWIG 6 PS (instead of PYTHIA 8)