NLO QCD and EW corrections
to processes involving off-shell top quarks

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Based on:

In collaboration with:
Ansgar Denner, Jean-Nicolas Lang and Sandro Uccirati

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1. Introduction

2. \( pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} \) at NLO EW
   - Presentation of the calculation
   - NLO EW corrections
   - Off-shell effects

3. \( pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b}H \) at NLO EW
   - Presentation of the calculation
   - NLO EW corrections
   - Combination with NLO QCD corrections

4. Conclusion
- Final states dominated by a production process
- Example: final state $e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}$ dominated by $pp \rightarrow t^* \bar{t}^* \rightarrow (W^* \rightarrow \nu_\mu \mu^-)(W^* \rightarrow e^+ \nu_e) b\bar{b}$

\[ d\sigma/dp_T \]

- **On-shell** region dominated by resonant production
- **Off-shell** region receives large non-resonant contributions
- Only $e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}$ is measured in experiments

$\rightarrow$ During run II, the tail of the distributions will be probed
$\rightarrow$ New physics contributions?
Electroweak (EW) corrections:

- Large in high energy region
- Sudakov logarithms: $-\frac{\alpha}{4\pi} \log^2 \left(\frac{s_{ij}}{M_W^2}\right)$

During run II, the tail of the distributions will be probed.

New physics contributions?
Top-quark pair production is a standard candle at the LHC

Need for precise theoretical predictions:

- **NLO QCD** [Melnikov, Schulze; 0907.3090], [Bevilacqua et al.; 1012.4230], [Denner et al.; 1207.5018], [Frederix; 1311.4893], [Campbell et al.; 1204.1513, 1608.03356], ...
- **NNLO QCD** [Czakon et al.; 1303.6254, 1601.05375, 1606.03350], [Gao, Papanastasiou; 1705.08903]
- **Resummation** [Beneke et al.; 0907.1443], [Czakon et al.; 0907.1790], [Ahrens et al.; 1003.5827], [Kidonakis; 0903.2561, 1009.4935]
- **NLO QCD matched to PS** [Frixione et al.; hep-ph/0305252, 0707.3088], [Höche et al.; 1402.6293], [Garzelli et al.; 1405.5859], [Campbell et al.; 1412.1828], [Ježo et al.; 1607.04538]

→ All the EW calculations have been done for on-shell top quarks
→ Calculation of NLO EW corrections to off-shell $t\bar{t}$ production:

$$pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$$

- Off-shell, non-resonant, and interference effects
  → Realistic final state
- EW corrections can be large in certain phase-space regions
  → Sudakov logarithms
- Theoretical and numerical challenge to consider $2 \rightarrow 6$ process
  → Up to 6 external charged particles and 4 intermediate resonances
The LO is defined at order $\mathcal{O}(\alpha_s^2 \alpha^4)$

- Not only doubly resonant top-pair contributions
- NLO EW corrections are of order $\mathcal{O}(\alpha_s^2 \alpha^5)$
  - Two types of virtual corrections
  - Interference of EW and QCD processes

- In the same way, interference channel: $gq/\bar{q} \to t^* \bar{t}^* q/\bar{q}$
- QCD corrections of photon induced $\mathcal{O}(\alpha_s \alpha^6): g\gamma \to t^* \bar{t}^*$
  (neglected here as Born contribution is already small)
→ **Tools / Techniques**

- **Tree and one-loop matrix element:**
  - **RECOLA** [Actis, Denner, Hofer, Lang, Scharf, Uccirati] + **COLLIER** [Denner, Dittmaier, Hofer]
- **In-house Monte Carlo - MoCaNLO** [Feger]
- **Dipole subtraction method** [Catani, Seymour], [Dittmaier]
- **Complex-mass scheme** [Denner et al.]
- **LHAPDF** [LHAPDF collaboration]

→ **Validation**

- **Tree-level matrix elements:** **MadGraph5_aMC@NLO** [Alwall et al.; 1405.0301]
- **Born hadronic cross sections:** **MadGraph5_aMC@NLO**
- **Virtual corrections:**
  - Double-Pole Approximation (automatised and checked for DY and di-boson)
  - Check of a Ward identity in **RECOLA** (internal check)
- **IR-subtraction/finiteness:**
  - Variation of $\alpha$ parameter [Nagy, Trosanyi; hep-ph/9806317]
  - Variation of technical cuts
  - Variation of IR-scale
Predictions for $\sqrt{s} = 13$ TeV at the LHC

→ NNPDF23_nlo_as_0119_qed [NNPDF Collaboration]
with massless bottom quarks and bottom-quark PDF neglected
→ Event selection:

  b jets: \( p_{T,b} > 25 \text{ GeV}, \quad |y_b| < 2.5 \)

  charged lepton: \( p_{T,\ell} > 20 \text{ GeV}, \quad |y_\ell| < 2.5 \)

  missing transverse momentum: \( p_{T,\text{miss}} > 20 \text{ GeV} \)

  b-jet–b-jet distance: \( \Delta R_{bb} > 0.4 \)

→ anti-\(k_T\) jet algorithm [Cacciari, Salam, Soyez]
with \( R = 0.4 \) for both jet clustering and photon recombination
Fiducial cross section

<table>
<thead>
<tr>
<th>Ch.</th>
<th>$\sigma_{LO}$ [fb]</th>
<th>$\sigma_{NLO EW}$ [fb]</th>
<th>$\delta$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>gg</td>
<td>2824.2(2)</td>
<td>2834.2(3)</td>
<td>0.35</td>
</tr>
<tr>
<td>$q\bar{q}$</td>
<td>375.29(1)</td>
<td>377.18(6)</td>
<td>0.50</td>
</tr>
<tr>
<td>$gq(\bar{q})$</td>
<td>0.259(4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma g$</td>
<td></td>
<td>27.930(1)</td>
<td></td>
</tr>
<tr>
<td>pp</td>
<td>3199.5(2)</td>
<td>3211.7(3)</td>
<td>0.38</td>
</tr>
</tbody>
</table>

- Cross section dominated by the gg channel
- $\gamma g$ channel around 1%
- Small positive EW corrections
  - Negative corrections for on-shell top quarks ($\sim -1.5\%$)
  (due to the choice of the top width)
\( \rightarrow \) Sudakov logarithms \( \rightarrow -15\% \)

\( \rightarrow \) Important photon contributions \( \rightarrow +6\% \) [Pagani, Tsinikos, Zaro; 1606.01915]
Radiative tail due to non-reconstructed photons
Double-Pole Approximation (DPA):
- Accounts for off-shell effects
  - Resonant propagator fully included / Full phase space
- Expansion about the resonance poles
- Applied only to the virtual corrections
  - Accounts for non-factorisable corrections

Two DPAs considered: \( t\bar{t} \) and \( WW \)
Introduction

\[ \text{pp} \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} \text{ at NLO EW} \]

\[ \text{pp} \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} H \text{ at NLO EW} \]

Conclusion

Presentation of the calculation

NLO EW corrections

Off-shell effects

<table>
<thead>
<tr>
<th>Ch.</th>
<th>( \sigma_{\text{LO}}^{\text{WW DPA}} ) [fb]</th>
<th>( \delta_{\text{LO}}^{\text{WW DPA}} ) [%]</th>
<th>( \sigma_{\text{LO}}^{\text{tt DPA}} ) [fb]</th>
<th>( \delta_{\text{LO}}^{\text{tt DPA}} ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( gg )</td>
<td>2808.4(6)</td>
<td>-0.56</td>
<td>2738.8(2)</td>
<td>-3.0</td>
</tr>
<tr>
<td>( q\bar{q} )</td>
<td>372.90(1)</td>
<td>-0.64</td>
<td>368.82(1)</td>
<td>-2.2</td>
</tr>
<tr>
<td>( pp )</td>
<td>3181.3(5)</td>
<td>-0.57</td>
<td>3107.6(2)</td>
<td>-2.9</td>
</tr>
</tbody>
</table>

\[ \rightarrow \text{At LO, WW DPA is better than the tt DPA} \]

<table>
<thead>
<tr>
<th>Ch.</th>
<th>( \sigma_{\text{NLO EW}}^{\text{WW DPA}} ) [fb]</th>
<th>( \delta_{\text{NLO EW}}^{\text{WW DPA}} ) [%]</th>
<th>( \sigma_{\text{NLO EW}}^{\text{tt DPA}} ) [fb]</th>
<th>( \delta_{\text{NLO EW}}^{\text{tt DPA}} ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( gg )</td>
<td>2832.9(2)</td>
<td>-0.046</td>
<td>2836.5(2)</td>
<td>+0.082</td>
</tr>
<tr>
<td>( q\bar{q} )</td>
<td>377.36(8)</td>
<td>0.047</td>
<td>377.23(5)</td>
<td>+0.013</td>
</tr>
<tr>
<td>( pp )</td>
<td>3210.5(2)</td>
<td>-0.037</td>
<td>3214.0(2)</td>
<td>+0.072</td>
</tr>
</tbody>
</table>

\[ \rightarrow \text{At NLO, both DPAs are equally good} \]
Both DPAs work well for top dominated observables.
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NLO QCD and EW corrections to processes involving off-shell top quarks

→ \textit{tt DPA is failing due to missing 0/1-top resonance contributions}
\[
pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} \text{ at NLO EW}
\]

\[
pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} H \text{ at NLO EW}
\]

**Introduction**

**Conclusion**

**Presentation of the calculation**

**NLO EW corrections**

**Off-shell effects**

\[
\frac{d\sigma}{dM_{\mu^- \bar{b}}} \left[ \text{fb} \right]
\]

<table>
<thead>
<tr>
<th>( M_{\mu^- \bar{b}} ) [GeV]</th>
<th>LO WW</th>
<th>NLO WW</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10^{-2}</td>
<td>10^{-1}</td>
</tr>
<tr>
<td>50</td>
<td>100</td>
<td>101</td>
</tr>
<tr>
<td>100</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>200</td>
<td>250</td>
<td>300</td>
</tr>
<tr>
<td>300</td>
<td>350</td>
<td>400</td>
</tr>
</tbody>
</table>

\[
\delta [\%]
\]

\[
M_{\mu^- \bar{b}} \left[ \text{GeV} \right]
\]

\rightarrow Kinematic edge: \( M_{\mu^- \bar{b}}^2 < M_t^2 - M_W^2 \simeq (154 \text{ GeV})^2 \)

\rightarrow Only full calculation reliable over the whole phase space for arbitrary distributions
**Need for precise predictions for $t\bar{t}H$ production:**

- **NLO QCD** [Beenakker et al.; hep-ph/0107081, hep-ph/0211352],

- **NLO EW** [Frixione et al.; 1407.0823, 1504.03446], [Zhang et al.; 1407.1110]

- **Resummation** [Broggio et al.; 1510.01914, 1611.00049, 1707.01803],
  [Kulesza et al.; 1509.02780, 1704.03363]

- **NLO QCD matched to PS** [Frederix et al.; 1104.5613], [Garzelli et al.; 1108.0387],
  [Hartanto et al.; 1501.04498]

- **NLO QCD for off-shell top quarks** [Denner, Feger; 1506.07448] (LHC),
  [Chokoufé-Nejad et al.; 1609.03390] (Linear collider)

→ NLO EW calculations for off-shell top quarks still missing
Calculation of NLO EW corrections to off-shell $t\bar{t}H$ production:

$$pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}H$$

- Off-shell, non-resonant, and interference effects
  - Realistic final state
- EW corrections can be large in certain phase space-regions
  - Sudakov logarithms
- Theoretical and numerical challenge to consider $2 \rightarrow 7$ process
  - Up to 6 external charged particles and 4 intermediate resonances
  - Virtual corrections involving up to 9-point functions
- Extension of two off-shell top quarks computations:
  - [Denner, Feger; 1506.07448] (NLO QCD to $t\bar{t}H$) and
  - [Denner, MP; 1607.05571] (NLO EW to $t\bar{t}$)
The LO is defined at order $\mathcal{O}\left(\alpha_s^2\alpha^5\right)$

→ Higgs-boson emission from any massive particle ($t$, $W$, and $Z$)

NLO EW corrections are of order $\mathcal{O}\left(\alpha_s^2\alpha^6\right)$

→ Inclusion of real and virtual contributions

→ Identical type of interferences and photon contributions
Fiducial cross section

<table>
<thead>
<tr>
<th>Ch.</th>
<th>$\sigma_{LO}$ [fb]</th>
<th>$\sigma_{NLO EW}$ [fb]</th>
<th>$\delta$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>gg</td>
<td>2.0116(1)</td>
<td>2.020(1)</td>
<td>+0.42</td>
</tr>
<tr>
<td>$q\bar{q}$</td>
<td>0.84860(5)</td>
<td>0.8454(6)</td>
<td>−0.38</td>
</tr>
<tr>
<td>$gq(\text{or }\bar{q})$</td>
<td>0.00007(2)</td>
<td>0.02178(1)</td>
<td></td>
</tr>
<tr>
<td>$\gamma g$</td>
<td>0.02178(1)</td>
<td>0.02178(1)</td>
<td></td>
</tr>
<tr>
<td>pp</td>
<td>2.8602(1)</td>
<td>2.866(1)</td>
<td>+0.20</td>
</tr>
</tbody>
</table>

- Cross section dominated by the gg channel
- $\gamma g$ channel below 1%
- $\rightarrow$ LUXqed\_plus\_PDF4LHC15\_nnlo\_100 [Manohar, Nason, Salam, Zanderighi]
- Small positive EW corrections
\[ pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} \text{ at NLO EW} \]

\[ pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} H \text{ at NLO EW} \]

\[ \delta [%] \]

\[ p_{T,\text{miss}} [\text{GeV}] \]

\[ d\sigma \]

\[ d\sigma \]

\[ \frac{d\sigma}{dp_{T,\text{miss}}} [\text{fb GeV}] \]

\[ \text{LO} \]

\[ \text{NLO EW} \]

\rightarrow \text{Sudakov logarithms} \rightarrow -8\%

\rightarrow \text{Limited photon contributions (around } +1\% \rightarrow \text{LUXqed PDF})
\[
\sigma_{\text{QCD}}^{\text{NLO}} = \sigma_{\text{Born}} + \delta\sigma_{\text{QCD}}^{\text{NLO}} \quad \text{and} \quad \sigma_{\text{EW}}^{\text{NLO}} = \sigma_{\text{Born}} + \delta\sigma_{\text{EW}}^{\text{NLO}}
\]

→ **Additive and multiplicative** combination:

\[
\sigma_{\text{QCD+EW}}^{\text{NLO}} = \sigma_{\text{Born}} + \delta\sigma_{\text{QCD}}^{\text{NLO}} + \delta\sigma_{\text{EW}}^{\text{NLO}}
\]

and

\[
\sigma_{\text{QCD\times EW}}^{\text{NLO}} = \sigma_{\text{QCD}}^{\text{NLO}} \left(1 + \frac{\delta\sigma_{\text{EW}}^{\text{NLO}}}{\sigma_{\text{Born}}}\right) = \sigma_{\text{EW}}^{\text{NLO}} \left(1 + \frac{\delta\sigma_{\text{QCD}}^{\text{NLO}}}{\sigma_{\text{Born}}}\right)
\]

→ **Results** (in \([\text{fb}]):\)

Recompute the QCD corrections of Ref. [Denner, Feger; 1506.07448] in the present set-up

<table>
<thead>
<tr>
<th>(\sigma_{\text{LO}})</th>
<th>(\sigma_{\text{Born}})</th>
<th>(\sigma_{\text{QCD}}^{\text{NLO}})</th>
<th>(\sigma_{\text{EW}}^{\text{NLO}})</th>
<th>(\sigma_{\text{QCD+EW}}^{\text{NLO}})</th>
<th>(\sigma_{\text{QCD\times EW}}^{\text{NLO}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4817(1)</td>
<td>2.7815(1)</td>
<td>2.866(1)</td>
<td>2.721(3)</td>
<td>2.806</td>
<td>2.804</td>
</tr>
</tbody>
</table>
→ NLO effects dominated by QCD corrections
\( \rightarrow \) Differences between the two combinations for large EW corrections
Summary

- First NLO EW calculation of the full off-shell processes $pp \rightarrow t^*\bar{t}^*$ and $pp \rightarrow t^*\bar{t}^*H$
- NLO EW corrections are non-negligible
  -> Between $+15\%$ and $-15\%$
- Off-shell effects can be large
  -> $WW$ approximation better than the $tt$ one
  -> Only the full calculation is always reliable
- Combination with NLO QCD corrections for $pp \rightarrow t^*\bar{t}^*H$
  -> State-of-the art predictions comparable with experiments

Introduction

pp → $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ at NLO EW

pp → $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}H$ at NLO EW

Conclusion

tth DPA

Back-up slides

BACK-UP
**Factorisable corrections**

\[
\mathcal{M}_{\text{virt, fact, PA}} = \sum_{\lambda_1, \ldots, \lambda_r} \left( \prod_{i=1}^{r} \frac{1}{K_i} \right) \left[ \mathcal{M}^{l \rightarrow N, \overline{R}} \prod_{j=1}^{r} \mathcal{M}^{j \rightarrow R_j}_{\text{LO}} \right.
\]

\[+ \mathcal{M}^{l \rightarrow N, \overline{R}} \sum_{k=1}^{r} \mathcal{M}^{k \rightarrow R_k}_{\text{virt}} \prod_{j \neq k}^{r} \mathcal{M}^{j \rightarrow R_j}_{\text{LO}} \right] \left\{ \frac{-k_i^2}{k_i^2} = M_i^2 \right\}_{l \in \overline{R}}
\]

**Non-factorisable corrections:**

\[
2\text{Re} \left\{ \mathcal{M}^{*}_{\text{LO, PA}} \mathcal{M}_{\text{virt, nfact, PA}} \right\} = |\mathcal{M}_{\text{LO, PA}}|^2 \delta_{\text{nfact}}
\]

**On-shell projection**

**DPA applied to virtual corrections and \( l \)-operator**

**Full Born and Real contributions:**
**Top width(s) for \( pp \rightarrow t^*\bar{t}^*H \)**

- \( \Gamma^\text{LO}_t = 1.449582 \text{ GeV} \)
  - Used for LO in the comparison with NLO QCD and EW
  - Crudest predictions

- \( \Gamma^\text{NLO,QCD}_t = 1.35029 \text{ GeV} \)
  - Used for LO in the comparison with NLO EW alone
  - To isolate EW effects

- \( \Gamma^\text{NLO}_t = 1.36918 \text{ GeV} \) (with both NLO QCD and EW corrections)
  - Used for NLOs (NLO EW alone or NLO QCD and EW together)
  - Best predictions

Taken from Ref. [Basso, Dittmaier, Huss, Oggero; 1507.04676]
Distributions full (1) for \( pp \rightarrow t^*\bar{t}^*H \)

\[ d\sigma \over dt^*\bar{t}^*H \]

\[ 10^{-2} \]

\[ 10^{-3} \]

\[ \delta \% \]

\[ \Delta \% \]

\[ +10\% \text{ to } -5\% \text{ over the whole range: non-negligible effect} \]
Distributions full (2) for $pp \rightarrow t^*\bar{t}^*H$
Distributions full (3) for $pp \rightarrow t^*\bar{t}^*H$
DPA distributions (1) for $pp \rightarrow t^*\bar{t}^*H$
DPA distributions (2) for $pp \rightarrow t^* \bar{t}^* H$
Combination distributions (1) for $pp \rightarrow t^*\bar{t}^*H$
Combination distributions (2) for $pp \rightarrow t^* \bar{t}^* H$
Real radiations for \( pp \rightarrow t^*\bar{t}^* \)

→ Photon radiation/ Gluon radiation / \( gq(\bar{q}) \) channel
Distributions full (2) for $pp \rightarrow t^*\bar{t}^*$
Distributions full (3) for pp → t^*\bar{t}^*
DPA distributions (1) for $pp \rightarrow t^*\bar{t}^*$

**Graph 1:**
- **Axes:** $p_T, b_1$ vs. $d \sigma/dp_T, b_1$ [fb GeV]
- **Legend:**
  - LO tt
  - LO WW
  - NLO tt
  - NLO WW

**Graph 2:**
- **Axes:** $p_T, e^+$ vs. $d \sigma/dp_T, e^+$ [fb GeV]
- **Legend:**
  - LO tt
  - LO WW
  - NLO tt
  - NLO WW

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NLO QCD and EW corrections to processes involving off-shell top quarks
DPA distributions (2) for $pp \rightarrow t^*\bar{t}^*$
Double-Pole Approximation (DPA):

→ Same principle but one extra Higgs boson
⇔ [Dittmaier, Schwan; 1511.01698], [Denner, MP; 1607.05571]

Two DPAs considered: \(tt\) and \(WW\)
### Introduction

\[ pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} \] at NLO EW

\[ pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}H \] at NLO EW

### Conclusion

- **Ch.**

<table>
<thead>
<tr>
<th>( \sigma_{\text{LO}} )</th>
<th>( \delta_{\text{LO}} )</th>
<th>( \sigma_{\text{NLO EW}} )</th>
<th>( \delta_{\text{NLO EW}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{gg} )</td>
<td>2.0003(1)</td>
<td>-0.56</td>
<td>1.9738(1)</td>
</tr>
<tr>
<td>( \text{q}\bar{q} )</td>
<td>0.8437(5)</td>
<td>-0.58</td>
<td>0.83640(5)</td>
</tr>
<tr>
<td>( \text{pp} )</td>
<td>2.8441(1)</td>
<td>-0.56</td>
<td>2.8102(1)</td>
</tr>
</tbody>
</table>

→ At LO, WW DPA is better than the tt DPA

- **Ch.**

<table>
<thead>
<tr>
<th>( \sigma_{\text{NLO EW}} )</th>
<th>( \delta_{\text{NLO EW}} )</th>
<th>( \sigma_{\text{NLO EW}} )</th>
<th>( \delta_{\text{NLO EW}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{gg} )</td>
<td>2.0237(6)</td>
<td>+0.18</td>
<td>2.0188(2)</td>
</tr>
<tr>
<td>( \text{q}\bar{q} )</td>
<td>0.8470(4)</td>
<td>+0.19</td>
<td>0.8446(4)</td>
</tr>
<tr>
<td>( \text{pp} )</td>
<td>2.8712(8)</td>
<td>+0.18</td>
<td>2.8639(4)</td>
</tr>
</tbody>
</table>

→ At NLO, both DPAs are equally good (DPA only applied to virtual)
Both DPAs work well for top dominated observables
→ tt DPA is failing due to missing 0/1-top resonance contributions
Only the full calculation is reliable over the whole phase space for arbitrary distributions (e.g. kinematic edges)