Theoretical Overview on Top Quark Physics

Malgorzata Worek
Instead of Introduction

- Simply list, page-by-page, latest theoretical results
  - Not only are they impressive, but there are plenty of them
- Tell story, hopefully interesting one
  - Concentrate on general structure of our predictions
  - Special case $tt \Rightarrow$ NNLO
  - $tt + X, X=H, \gamma, W, Z, j, jj, bb, tt, \gamma\gamma, \ldots \Rightarrow$ NLO

My Goal

- Identify which effects are important & should be taken into account
- Few examples
- Vital for SM top quark physics studies & BSM searches & SM Higgs boson measurements $\Rightarrow$ $ttH$

- (Biased) Selection $\Rightarrow$ Only latest 2020 & 2021 results $\Rightarrow$ Only LHC results
**Instead of Introduction**

- **SM** ⇨ Extremely fun & exciting & enjoyable time for people working on $QCD + EW$

- **BSM** ⇨ Significant number of open questions remains & Search for new phenomena key aspect of LHC

**BSM Direct Searches**
- Many proposals for New Physics
- No model of New Physics really stands out ⇨ No obvious candidates to look for @ LHC

**BSM Indirect Searches**
- New Physics can be seen as small corrections to SM reactions
- *Precision SM measurements @ LHC ⇨ BSM Physics ⇨ High Luminosity LHC*
- Fully exploit experimental program ⇨ *High Precision Theoretical Predictions ⇨ Top Quark*
Unlike Other Quarks

- **Top Quark** $\Rightarrow$ Discovered at TeVatron in 1995
- Heaviest observed particle

$$m_t = (173.34 \pm 0.76) \text{ GeV}$$

- Substantial Yukawa coupling $\Rightarrow$ Special relation with SM Higgs boson

$$Y_t = \sqrt{2} \frac{m_t}{v} \approx 1$$

- Short lifetime $\Rightarrow$ Decay before bound states can be formed

- Direct handle on top-quark properties from its decay products

$$b - jets, p_T^{miss}, \ell^{\pm} & light - jets$$
## LHC as Top Quark Factory

### LHC Run 1
- **LHC\(_7\) TeV**
  - \(\sigma_{tt} \text{ [pb]}\): 180
  - \(L \text{ [fb}^{-1}]\): 5.0
  - \(N_{\text{event}}\): \(9 \times 10^5\)
- **LHC\(_8\) TeV**
  - \(\sigma_{tt} \text{ [pb]}\): 256
  - \(L \text{ [fb}^{-1}]\): 19.7
  - \(N_{\text{event}}\): \(5 \times 10^6\)
- **LHC\(_{13}\) TeV**
  - \(\sigma_{tt} \text{ [pb]}\): 835
  - \(L \text{ [fb}^{-1}]\): 139
  - \(N_{\text{event}}\): \(1 \times 10^8\)

### LHC Run 2
- **HL-LHC\(_{14}\) TeV**
  - \(\sigma_{tt} \text{ [pb]}\): 987
  - \(L \text{ [fb}^{-1}]\): 3000
  - \(N_{\text{event}}\): \(3 \times 10^9\)
- **HE-LHC\(_{27}\) TeV**
  - \(\sigma_{tt} \text{ [pb]}\): 3840
  - \(L \text{ [fb}^{-1}]\): 15000
  - \(N_{\text{event}}\): \(6 \times 10^{10}\)

### ATLAS & CMS
- Statistics doubled
- *HL-LHC*

---

Top quark pair production @ NNLO QCD with \(\text{TOP++}\)
- CT14nnlo PDF
- \(m_t = 173.2 \text{ GeV}\)

\[
\mu_R = \mu_F = \frac{1}{2} m_t
\]

Theoretical uncertainties:
- NNLO QCD: 5% - 6%
- NNLO QCD + NNLL: 3% - 4%

*Czakon, Mitov '14*
Both can be Probe with Top Quark

Precision Top-Quark Physics @ LHC
- Infrared structure of $QCD$
- Electroweak sector of SM

Precision Top-Quark physics & BSM Direct Searches
- No sign of New Physics in TeV range
- Search for new phenomena with (simplified)-models involving tops $\Rightarrow tt + DM$
- $tt (+ X) \Rightarrow$ Main backgrounds to many BSM scenarios

Precision Top-Quark physics & BSM Indirect Searches
- Various production modes & decay channels & properties & rare decays & …
- Extract SM parameters, constraining PDFs, verify Higgs boson couplings to top quarks & …
- Study very specific infra-red safe observables as precisely as possible

Discrepancies between Precise measurements & Precise Theory
- Find hints of new physics in LHC data
**Top-Quark Pair Production @ NNLO + NNLL**

- **LHC & Tevatron** ⇒ $\sigma_{tt}$ as function of $\sqrt{s}$
- **NNLO QCD + NNLL** ⇒ **Top++2.0**

  * Czakon, Mitov '14

- Theory uncertainties due to $\mu_R$ & $\mu_F$ & PDF
- Measurements & theory for $m_t = 172.5$ GeV

  * Czakon, Fiedler, Mitov '13

  * Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Sargsyan '19

- **NNLO QCD** with all-order radiative corrections as implemented via parton-shower simulations

  * Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi '21
### Top-Quark Pair Production & Decay @ NNLO

\[ \frac{d\sigma}{dt} = d\sigma^{LO} + \alpha_s d\sigma^{NLO} + \alpha_s^2 d\sigma^{NNLO} \]

- Predictions in NWA

\[ d\sigma^{LO} = \sigma^{LOxLO}, \]
\[ d\sigma^{NLO} = d\sigma^{NLOxLO} + d\sigma^{LOxNLO} - \frac{2\Gamma_t^{(1)}}{\Gamma_t^{(0)}} d\sigma^{LO}, \]
\[ d\sigma^{NNLO} = d\sigma^{NLOxLO} + d\sigma^{NLOxNLO} + d\sigma^{LOxNNLO} - \frac{2\Gamma_t^{(1)}}{\Gamma_t^{(0)}} d\sigma^{NLO} + \left( \frac{3\Gamma_t^{(1)})^2}{\Gamma_t^{(0)2}} - \frac{2\Gamma_t^{(0)}\Gamma_t^{(2)}}{\Gamma_t^{(0)2}} \right) d\sigma^{LO} \]

\[ pp \to t\bar{t} + X \to W^+W^-b\bar{b} + X \to \ell^+\nu_{\ell^-}\ell^-\bar{\nu}_{\ell}b\bar{b} + X \]

---

**Di-lepton**

Czakon, Mitov, Poncelet ’19

---

**Graph:**

- LHC 13 TeV, \( m_t = 172.5 \text{ GeV} \)
- Scale: \( H_T/4 \) PDF: NNPDF31

**Legend:**

- LO
- NLO
- ATLAS

**Axes:**

- \( \Delta \phi(\ell\ell)/\pi \)
- Ratio to NLO

**Data Points:**

- Various data points indicating the comparison of theoretical predictions with experimental data.
ATLAS & CMS data
Compared to **Powheg-Box+Pythia8**
Compared to NNLO QCD

Higher order corrections in production & decay important
**TT+X Production & Decay @ NLO**

- **NNLO QCD** theoretical predictions only for $tt$
- More exclusive final states produced @ LHC

---

**Helac-Nlo**

**LHCTopWG**

**Helac-Phegas**

$m_t = 173.2$ GeV

CT14llo PDF

**Cafarella, Papadopoulos, Worek ‘09**

**ATLAS+CMS**

**Preliminary**

\[ \sigma_{tt} = 0.55^{+0.15}_{-0.15} \text{(scale)} \times 0.01 (\text{PDF}) \text{ pb} \]

\[ \sigma_{t\bar{t}Z} = 0.86^{+0.07}_{-0.09} (\text{scale}) \times 0.02 (\text{PDF}) \text{ pb} \]

**Helac-Phegas**

**Bevilacqua, Hartanto, Kraus, Weber, Worek ‘18**


NLO(QCD+EW)+NNLL

**JHEP 10 (2018) 158**

NLO(QCD)

**ATLAS, L = 36.1 fb^{-1}**

**CMS, L = 35.9 fb^{-1}**

**JHEP 09 (2019) 072009**

**JHEP 08 (2018) 011**

**ATLAS, L = 139 fb^{-1}**

**CMS, L = 77.5 fb^{-1}**

**JHEP 03 (2020) 056**

**ATLAS, L = 139 fb^{-1}, Vis 1**

**CMS, L = 137 fb^{-1}, Vis 2**

**arXiv:2107.01508**

\( \sigma_{t\bar{t} + tW} = 0.040 \pm 0.001^{+0.009}_{-0.008} \text{ pb} \times 20 \)

\( \sigma_{t\bar{t}Y} = 0.80 \pm 0.01 \pm 0.05 \text{ pb} \)

---

\( \sqrt{s} = 13 \text{ TeV} \)

September 2021

\( m_t = 173.2 \text{ GeV} \)

CT14llo PDF
Higher order corrections to production & decays important
Theoretical Predictions for $TT + X$

- NLO corrections for stable top quarks
  - General idea about size of NLO corrections.
  - Can not provide reliable description of top quark decay products and radiation pattern
    - NLO QCD
    - NLO Electro-Weak

- For more realistic studies decays are needed:
  - NLO QCD for $TT + X + PS$
  - NLO QCD for $TT + X + LO Decays + PS$
  - NLO QCD in NWA
  - NLO QCD Complete Off-shell Effects
Definition with TTW

**Full/Complete Off-shell Effects**

- **Complete Off-shell Effects:**
  - Off-shell $t$ & $W$ described by Breit-Wigner propagators
  - Double-, single- & non-resonant top-quark contributions included
  - All interference effects incorporated at matrix element level
  - NLO QCD corrections to production & decays
  - Nonfactorizable NLO QCD corrections included ⇒ Cross-talk between production & decays
  - NLO spin correlations

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

\[
pp \rightarrow e^-\bar{\nu}_e \mu^+ \nu_\mu e^-\bar{\nu}_e b\bar{b} + X
\]
**Definition with TTW**

- **Narrow Width Approximation (NWA)**

  - **NWA:**
    - Works in the limit \( \Gamma_t/m_t \to 0 \)
    - Incorporates only double resonant contributions
    - Restricts unstable \( t \) & \( W \) to on-shell states

    - NLO QCD correction separately to production & separately to decays
    - NLO QCD nonfactorizable corrections missing \( \Leftrightarrow \) No cross-talk between production & decays
    - NLO spin correlations

- **NWA with LO Decays (NWA_{LODEC})**
  - Without NLO QCD corrections to top decays
  - LO spin correlations

- \( \Gamma_t = 1.35159 \text{ GeV}, \ m_t = 173.2 \text{ GeV}, \ \Gamma_t/m_t \approx 0.008 \)

\[
\begin{align*}
\frac{\Gamma_W}{m_W} & > \frac{\Gamma_t}{m_t} \gg \frac{\Gamma_H}{m_H}, \\
2.6\% & > 0.8\% \gg 0.003\%.
\end{align*}
\]

\[ pp \to ttW^+ + X \to W^+W^+W^-b\bar{b} + X \to e^+\nu_e \mu^-\bar{\nu}_\mu e^+\nu_e b\bar{b} \]
**Definition with TTW**

- **NLO + PS**

- NLO QCD corrections to stable $t$ & $W$ matched to parton shower programs
  - Without NLO QCD corrections to decays

- Decays via parton shower $\Rightarrow$ Without spin correlations

- Decays using LO matrix element
  - Double resonant contributions only
  - Breit-Wigner propagators for $t$ & $W$ with some cut-off
  - LO spin correlations
  - Single & non-resonant contributions for $t$ & $W$ are still missing

---

**Powheg-Box**

MG5_aMC@NLO

**Powheg-Box + LO Decays**

MG5_aMC@NLO + MadSpin

Cordero, Kraus, Reina ’21
Frederix, Tsinikos ’20
TTW Various Results

Multi-lepton

QCD

EW

Combined

Bevilacqua, Bi, Cordero, Hartanto, Kraus, Nasufi, Reina, Worek ‘21
**TTW How Good Is the NWA?**

**Di-lepton**

\[ H_T^{vis} = p_T(\mu^-) + p_T(\ell_1) + p_T(\ell_2) + p_T(j_b) + p_T(j_{b'}) \]

**Integrated level:**
- Complete top-quark off-shell effects 0.2%
- NLO QCD corrections to decays 3%-5%

**Differential level:**
- Off-shell up to 60% - 70%
- Substantial differences between NWA & NWA\_LOdecay

**Off-shell & NWA & NWA\_LOdecay**

\[ pp \rightarrow e^+\nu_e \mu^-\bar{\nu}_\mu e^+\nu_e \bar{b} \bar{b} + X \]
**Off-shell ttW**

**Di-lepton**

- **Fixed scale choice**  ⇒  Leads to perturbative instabilities in TeV region of differential cross & Large distortions
- **Dynamical scale choice**  ⇒  Stabilises tails & keeps NLO uncertainties bands within LO ones
How Good Is the NWA?

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

**Dimensionful observables**

- Sensitive to non-factorizable top quark corrections
- Tens of per cent in specific phase-space regions
- Kinematical edges & high \( p_T \) regions

*Bevilacqua, Hartanto, Kraus, Weber, Worek ’20*
Various Phase-space Regions

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

- **Full Off-shell Effects:**
  - High \( p_T \) region of various dimensionful observables
  - Vicinity of kinematical edges
  - Effects up to 50\% – 60\%

*Bevilacqua, Hartanto, Kraus, Weber, Worek '20*
**Dark Matter Searches @ LHC**

- **BSM:** Kinematical edges & high $p_T$ regions
- **$tt + DM$** $\Rightarrow$ QCD backgrounds: $tt$ & $ttZ$
- **Observable** $\Rightarrow M_{T2,W}$ & $M_{T2,t}$ & $p_{Tmiss}$

**Before & after applying additional cuts**

<table>
<thead>
<tr>
<th>Process</th>
<th>Order</th>
<th>Scale</th>
<th>$\sigma_{uncut}$ [fb]</th>
<th>$\sigma_{cut}$ [fb]</th>
<th>$\sigma_{cut}/\sigma_{uncut}$</th>
<th>Events for $L = 300$ fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tt$ NWA</td>
<td>LO</td>
<td>$H_T/4$</td>
<td>1061</td>
<td>0</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>LO</td>
<td>$E_T/4$</td>
<td>984</td>
<td>0</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>LO</td>
<td>$m_t$</td>
<td>854</td>
<td>0</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>NLO</td>
<td>$H_T/4$</td>
<td>1097</td>
<td>0</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>NLO, LO dec</td>
<td>$H_T/4$</td>
<td>1271</td>
<td>0</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>$ttZ$ NWA</td>
<td>LO</td>
<td>$H_T/3$</td>
<td>0.1223</td>
<td>0.0130</td>
<td>11%</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>LO</td>
<td>$E_T/3$</td>
<td>0.1052</td>
<td>0.0116</td>
<td>11%</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>LO</td>
<td>$m_{t} + m_\gamma/2$</td>
<td>0.1094</td>
<td>0.0134</td>
<td>12%</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>NLO</td>
<td>$H_T/3$</td>
<td>0.1226</td>
<td>0.0130</td>
<td>11%</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>NLO, LO dec</td>
<td>$H_T/3$</td>
<td>0.1364</td>
<td>0.0140</td>
<td>10%</td>
<td>50</td>
</tr>
<tr>
<td>$tt$ Off-shell</td>
<td>LO</td>
<td>$H_T/4$</td>
<td>1067</td>
<td>0.0144</td>
<td>0.0013%</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>LO</td>
<td>$E_T/4$</td>
<td>989</td>
<td>0.0131</td>
<td>0.0013%</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>LO</td>
<td>$m_t$</td>
<td>861</td>
<td>0.0150</td>
<td>0.0017%</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>NLO</td>
<td>$H_T/4$</td>
<td>1101</td>
<td>0.0156</td>
<td>0.0014%</td>
<td>19</td>
</tr>
<tr>
<td>$ttZ$ Off-shell</td>
<td>LO</td>
<td>$H_T/3$</td>
<td>0.1262</td>
<td>0.0135</td>
<td>11%</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>LO</td>
<td>$E_T/3$</td>
<td>0.1042</td>
<td>0.0115</td>
<td>11%</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>LO</td>
<td>$m_{t} + m_\gamma/2$</td>
<td>0.1135</td>
<td>0.0140</td>
<td>12%</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>NLO</td>
<td>$H_T/3$</td>
<td>0.1269</td>
<td>0.0134</td>
<td>11%</td>
<td>48</td>
</tr>
</tbody>
</table>

- After cuts 25% of events come from $tt$
- NLO smaller uncertainties w.r.t LO, NLO + PS & NLO + LO decays
Summary

- Proper modeling of top quark production & decay essential already now in presence of inclusive cuts:
  - NLO QCD corrections to $tt+X$
    1. Corrections to production & decays important ⇒ NLO $tt$ spin correlations
    2. Possibility of using kinematic-dependent $\mu_R$ & $\mu_F$ scales important
    3. Complete off-shell effects important

- Even more important for:
  - Exclusive cuts & High luminosity measurements
  - New Physics searches & Exclusion limits
  - SM parameter extraction

- Top quarks play important role in virtually every LHC analysis ⇒ SM & BSM

- Lots of data, sophisticated analyses, precision measurements ⇒ Should be compared to state-of-the-art theoretical predictions

- Full off-shell results for $tt$, $ttj$, $tty$, $ttZ$, $ttW^{\pm}$, $ttbb$ & $ttH$ (+ H decays in NWA) with HELAC-NLO
  - Stored ⇒ Ntuples Files ⇒ Les Houches & ROOT Files
  - Can be used by ATLAS & CMS
  - Should be matched to parton shower program