Multi-jet merged top-pair production including EW corrections

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Top Quark Physics at the Precision Frontier
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Top quark $p_T$

“the devil is in the tails”

Hadronic top (single lepton channel)

Leptonic top (dilepton channel)

Upshot:

NNLO QCD + NLO EW corrections important
But do not fully explain discrepancy
Tails of Tops

For tops: to add EW (and possibly NNLO?)

Decay: if feasible, may add some NNLO corrections

Assess the advantage of calorimeter upgrade (extended lepton tracking/b-tagging)

\[ \text{Cumulative in } \mu_H \]

\[ \text{Cumulative in } \mu_T \]

\[ \text{shown is: cumulative times max luminosity} \]

\[ \text{for tops: to add EW (and possibly NNLO?)} \]

\[ \text{decay: if feasible, may add some NNLO corrections} \]

\[ \text{assess the advantage of calorimeter upgrade (extended lepton tracking/b-tagging)} \]

\[ \text{14 TeV} \]

\[ \text{14 TeV} \]

\[ \text{27 TeV} \]

\[ \text{27 TeV} \]

\[ \text{slide by Alex Mitov} \]

\[ \text{1000 events} \]

\[ \text{1000 events} \]

\[ \text{100 events} \]

\[ \text{10 events} \]

\[ \text{1 event} \]

\[ \text{100 events} \]

\[ \text{10 events} \]

\[ \text{1 event} \]

\[ \text{1-10\% precision for } M_{tt} = 5000-6000 \text{ GeV} \]

\[ \text{1-10\% precision for } p_{T_{\text{top}}} = 2000-2500 \text{ GeV} \]

\[ \text{[M. Zaro, HL/HE LHC workshop, June 2018]} \]
QCD precision for top tails

- 1-10% precision for $M_{tt}=5000-6000 \text{ GeV}$
- 1-10% precision for $p_{T_{\text{top}}}=2000-2500 \text{ GeV}$

NNLO+NNLL' for top-pair production [Czakon et. al., '18]

- most relevant hard scale is not $M_{tt}$ itself but rather $H_T$
- remaining scale uncertainties at the level of 5%

- remaining scale uncertainties in the tail at the level of 5-10%

![Graph showing QCD precision for top tails with NNLO+NNLL' calculations.

Figure 4: Results for the absolute (left) and normalized (right) top-pair invariant mass distributions.

Figure 6: Comparison of NNLO and NNLO+NNLL calculations at LHC 13 TeV.
EW corrections for top-pair production

Origin: soft/collinear logs from virtual EW gauge boson (EW Sudakov logarithms)

- NLO EW: ~-12% at pT=1 TeV
- LO_{11} + LO_{02}: ~1%
- NLO_{12} + NLO_{03}: < 1%
EW corrections for top-pair production

- **NLO EW**: ~5% at $M_{tt}=2$ TeV
- **LO$_{11}$+LO$_{02}$**: ~2-3% at $M_{tt}=2$ TeV
- **NLO$_{12}$+NLO$_{03}$**: ~1% at $M_{tt}=2$ TeV
EW corrections: sqrtS dependence
8 TeV vs. 13 TeV

- $gg$ channel receives smaller EW corrections in Sudakov limit than $q\bar{q}$ channel, at 1 TeV:
  \[ \delta_{q\bar{q}}^{EW,sud} \approx 1.5 \delta_{gg}^{EW,sud} \]
- composition of total from $gg$ vs $q\bar{q}$ channels changes
  \[ \rightarrow \text{NLO EW correction changes} \]
  \[ \rightarrow \text{effect still small} \]
EW corrections: sqrtS dependence
8 TeV vs. 13 TeV
The additive and multiplicative approaches is completely negligible compared to their scale almost of the same size for the LUXQED uncertainty of variation. This is particularly relevant for the tail of the uncertainty. Therefore, besides the kinematic region where Sudakov e

The last inset shows a comparison of the ratio that

Additive combination

\[ \sigma_{\text{QCD+EW}} = \sigma_{\text{LO}}^\text{QCD} + \delta_{\text{NNLO}}^\text{QCD} + \delta_{\text{NLO}}^\text{EW} \]

Multiplicative combination

\[ \sigma_{\text{QCD\times EW}} = \sigma_{\text{LO}}^\text{QCD} \left(1 + \frac{\delta_{\text{NLO}}^\text{EW}}{\sigma_{\text{LO}}^\text{QCD}}\right) \] (try to capture some contributions, e.g. EW Sudakov logs × soft QCD)

Combination of QCD and EW corrections

Difference between these two approaches indicates size of missing mixed EW-QCD corrections: few percent
Mixed QCD-EW uncertainties

**Bold estimate:**

Consider real $\mathcal{O}(\alpha_s^2)$ correction to $t\bar{t}+1$jet

\[ \approx \text{NLO EW} \text{ to } t\bar{t}+1\text{jets} \]

and we observe

\[ \frac{d\sigma_{\text{EW,NLO}}}{d\sigma_{\text{LO}}} |_{t\bar{t}+1\text{jet}} - \frac{d\sigma_{\text{EW,NLO}}}{d\sigma_{\text{LO}}} |_{t\bar{t}} \lesssim 2\% \]

strong support for

- factorization
- multiplicative QCD x EW combination
Comparison with data

EW corrections alleviates tension with data

-10
-5
0
5
10
100
1000
35.8 fb\(^{-1}\) (13 TeV)

CMS

\(\frac{d\sigma}{dp_T(t_h)} [\text{pb GeV}^{-1}]\)

\(\frac{\text{Theory}}{\text{Data}}\)

\(p_T(t_h) [\text{GeV}]\)

Data

Sys \oplus \text{stat}

Stat

POWHEG P8

NNLO QCD+NLO EW

POWHEG H++

MG5 P8 [FxFx]

\(\sigma_{\text{stat}}(13 \text{ TeV})\)

\(\sigma_{\text{H++}}\)

\(\sigma_{\text{NNLO+NNLL'}}(\text{LUXQED17})\)

arXiv:1803.08856
EW corrections in particle-level event generation

• incorporate approximate electroweak corrections in SHERPA’s NLO QCD multijet merging (MEPS@NLO)

• modify MC@NLO B-function to include NLO EW virtual corrections and integrated approx. real corrections

\[ \overline{B}_{n,\text{QCD+EW}_{\text{virt}}}(\Phi_n) = \overline{B}_{n,\text{QCD}}(\Phi_n) + V_{n,\text{EW}}(\Phi_n) + I_{n,\text{EW}}(\Phi_n) + B_{n,\text{mix}}(\Phi_n) \]

optionally include subleading Born \( \text{LO}_{11}(+\text{LO}_{02}) \)

exact virtual contribution

approximate integrated real contribution
EW corrections in particle-level event generation

\[
\bar{B}_{n,\text{QCD+EW}_{\text{virt}}} (\Phi_n) = \bar{B}_{n,\text{QCD}} (\Phi_n) + V_{n,\text{EW}} (\Phi_n) + I_{n,\text{EW}} (\Phi_n) + B_{n,\text{mix}} (\Phi_n)
\]

optionally include subleading Born \( \text{LO}_{11}(+\text{LO}_{02}) \)

exact virtual contribution

approximate integrated real contribution

For pT-top: approximation reliable at 1%‐level

• real QED radiation can be recovered through standard tools (parton shower, YFS resummation)

⇒ simple stand-in for proper QCD+EW matching and merging (work-in-progress)
Results: $t\bar{t}+\text{jets} @ \text{MEPS NLO QCD+EW}_\text{virt}$ (0, 1 jets merged)

$pp \rightarrow t\bar{t} + 0,1(,2,3,4)$ jets at 13 TeV

$\frac{d\sigma}{d m_{t\bar{t}}}[\text{pb GeV}^{-1}]$

$\frac{1}{\text{MEPS@NLO QCD}}$

$10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^0$ $10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$

$m_{t\bar{t}} [\text{GeV}]$

$500$ $1000$ $1500$ $2000$ $2500$ $3000$ $3500$ $4000$ $4500$ $5000$

$pp \rightarrow t\bar{t} + 0,1(,2,3,4)$ jets at 13 TeV

$\frac{d\sigma}{d p_{T,t}}[\text{pb GeV}^{-1}]$

$\frac{1}{\text{MEPS@NLO QCD}}$

$10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^0$ $10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$

$p_{T,t} [\text{GeV}]$

$50$ $100$ $150$ $200$ $250$ $300$ $350$ $400$ $450$ $500$ $550$ $600$ $650$ $700$ $750$ $800$ $850$ $900$ $950$ $1000$

$\Rightarrow$ reproduces well the corrections seen at fixed-order
Results: ttbar+jets @ MEPS NLO QCD+EW_{virt} (0, 1 jets merged)

CKKW-scale with:
\[
\mu_{\text{core}} = \frac{1}{2} \left( \frac{1}{\hat{s}} + \frac{1}{m_t^2 - \hat{t}} + \frac{1}{m_t^2 - \hat{u}} \right)^{-\frac{1}{2}}
\]

- \[ pp \to t\bar{t} + 0, 1j@NLO \]
  \[ + 2, 3, 4j@LO \]

- additional LO multiplicities inherit electroweak corrections through MENLOPS differential \( K \)-factor

Höche, Krauss, MS, Siegert
\[ \text{arXiv:1009.1127} \]

- improved description of data
MEPS @ NLO vs. NNLO

[Czakon, JML, et. al., ‘18]

- MEPS@NLO and NNLO agree within uncertainties
- largely reduced uncertainties at NNLO
- shape differences

• EW corrections in MEPS NLO $\text{QCD}+\text{EW}_{\text{virt}}$
  agree with NNLO $\text{QCDxEW}$
MEPS @ NLO vs. NNLO

[Figure 2: Comparison between MEPS@NLO and NNLO predictions for the $p_T(t_1)$ and $p_T(t_2)$.]

Both approaches correctly take into account the contributions from one hard real emission at one-loop and two hard real emissions at tree level; a possible origin of the discrepancy may be due to the missing two-loop terms in the MEPS@NLO and/or the missing shower effects in the NNLO.

4 Conclusions and Outlook

In this proceeding we have compared two different approximations for phenomenological predictions of top-quark pair production at the LHC: NNLO QCD combined with EW corrections at NLO, and MEPS@NLO multi-jet merging at NLO also including EW corrections.

We have considered different distributions at 13 TeV: $p_T(t)$, $p_T$, $avt$, $p_T(t_1)$, $p_T(t_2)$ and $m(tt)$. In the case of $p_T(t)$ and $p_T$, the two approximations are compatible and, as expected, NNLO predictions have much smaller scale uncertainties. Thus, this approximation is more suitable for precision studies on parton-level distributions. On the other hand, fixed-order calculations can be pathological and indeed this is the case for $p_T(t_1)$ and $p_T(t_2)$ distributions in the regions $p_T(t_1)$ and $m(t)$ and $p_T(t_2)$, respectively, where the MEPS@NLO is superior to fixed-order calculations.

We have also shown that the relative effects induced by EW corrections in MEPS@NLO is much closer to those observed at NNLO with EW corrections combined in the multiplicative approach than in the case when they are simply added (additive approach).

For the specific case of $m(tt)$ a tension between the two approaches is present, especially for trailing top large uncertainties at fixed-order.
MEPS @ NLO vs. NNLO

- relevant difference between MEPS@NLO and NNLO for $M_{t\bar{t}}$
- MEPS@NLO (Sherpa) consistent with FxFx (MadGraph_aMC@NLO)

Figure 3: Comparison between MEPS@NLO and NNLO predictions (left) and between purely QCD MEPS@NLO, FxFx and NNLO predictions (right) for the $m(t\bar{t})$ distribution.

We conclude that an NNLO+PS calculation would be desirable for precise predictions in the full phase-space and especially for future studies. For this purpose, we remark the relevance of EW corrections and we have further supported the superiority of the multiplicative approach for their combination with those from QCD origin, especially in the boosted regime.

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[Czakon, JML, et. al., ’18]
Top-pair: off-shell NLO EW

[Denner, Pellen; ‘16]

Technical challenge: full $2 \rightarrow 6$ process, i.e. $pp \rightarrow \bar{t}b\ e^+\nu_e\mu^-\nu_\mu$ @ NLO EW (*)

- O(2-5%) around top resonance
- possible relevance for top mass measurements

- typical Sudakov behaviour O(10%) for $p_T, t = 800$ GeV
- LO non-resonant: 5% for $p_T, t = 800$ GeV

- non-resonant configurations can be relevant
- well described by WWbb approximation

![Diagram of top-pair production](image)
Conclusions

• Theory predictions for differential top production very advanced:
  
  NNLO QCD x NLO EW

• EW corrections relevant for pT-tails (and eventually also Mtt)

• ttbar and ttbar+ j now known at NLO including all one-loop orders:
  
  universal corrections observed

• Inclusion of approximate EW corrections in MEPS@NLO available

• Improves data description for boosted top quarks already at 8 TeV

• MEPS@NLO vs. NNLO differences to be understood

• publically available in Sherpa-2.2.5 & OpenLoops2
Backup
Scale setting

\[ \mu = \frac{m_T(t)}{2} \quad \text{for the } p_T(t) \text{ distribution,} \]

\[ \mu = \frac{m_T(\bar{t})}{2} \quad \text{for the } p_T(\bar{t}) \text{ distribution,} \]

\[ \mu = \frac{H_T}{4} = \frac{1}{4} (m_T(t) + m_T(\bar{t})) \quad \text{for all other distributions,} \]

In MEPS@NLO CKKW-scale with:

\[ \mu_{\text{core}} = \frac{1}{2} \left( \frac{1}{\hat{s}} + \frac{1}{m_t^2 - t} + \frac{1}{m_t^2 - \hat{u}} \right)^{-\frac{1}{2}} \]

\[ \mu_{\text{core}} \to \frac{1}{2} \sqrt{\frac{4}{5}} p_T \sim \frac{p_T}{2}, \]

\[ \mu_{\text{core}} \to \frac{m_T}{2} \sim \frac{H_T}{4}, \]

\[ \mu_{\text{core}} \to \frac{1}{2} \sqrt{\frac{4}{5}} m_t \sim \frac{H_T}{4}, \]

for \( p_T(t) \to \infty \)

for \( E(t) \to \infty \) and \( p_T(t)/E(t) \to 0 \)

for \( E(t) \to 0 \)