Off-Shell $t\bar{t}j$ Production and Top Quark Mass Measurement

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Outline

Next-to-Leading Order QCD predictions for:

$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$$

Outline:

- Introduction
- Results for LHC 13 TeV
- Comparison with Narrow Width Approximation (NWA)
- Top-quark mass extraction
- Conclusions

$t\bar{t}j$ production at the LHC

- At LHC, tops are produced with large energies and high p_T
- Increase probability to radiate gluons
- How big is the $t\bar{t}j$ contribution in the $t\bar{t}$ inclusive sample?

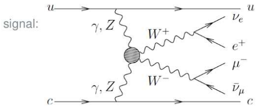
$\Rightarrow$ NLO $t\bar{t}$ cross section for $m_t = 173.2$ GeV at LHC 13 TeV with CT14 PDF

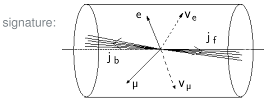
$$\sigma(t\bar{t}) = 715.58 \text{ pb}$$

Jet p_T cut [GeV]	$\sigma(t\bar{t}j)$ [pb]	$\sigma(t\bar{t}j)/\sigma(t\bar{t})$ [%]
40	296.97 ± 0.29	41
60	207.88 ± 0.19	29
80	152.89 ± 0.13	21
100	115.60 ± 0.14	16
120	89.05 ± 0.10	12

$t\bar{t}j$ as background

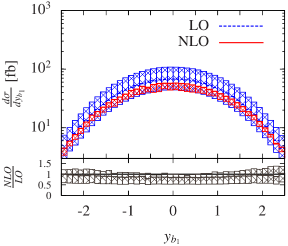
- Background for SM Higgs production in VBF: $qq \to Hqq \to WWqq$

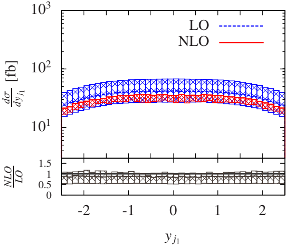




- VBF cut requires 2 tagging jets: $\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4$ and $y_{j_1} \times y_{j_2} < 0$
- In $t\bar{t}$ (+jets), b jets from tops are central, with VBF cut:

$\Downarrow$ $t\bar{t}$ background: $t\bar{t} \to WWb\bar{b}$, $\Uparrow$ $t\bar{t}j$ background: $t\bar{t}j \to WWb\bar{b}j$

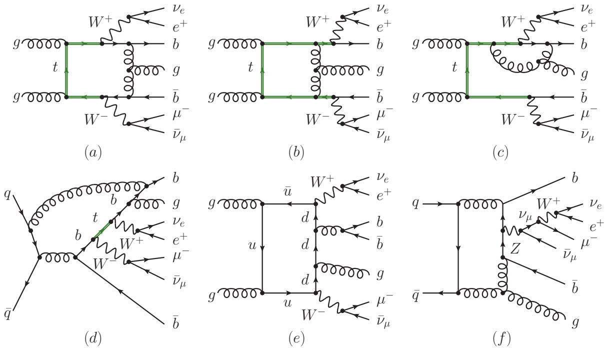




also background for SUSY or BSM searches with $\ell_1^+ \ell_2^-$ + MET + jets signature

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$: full calculation

$t\bar{t}j$ production at NLO QCD with tops decay leptonically $\mathcal{O}(\alpha_s^4\alpha^4)$



Calculation with HELAC-NLO framework

- Virtual corrections: HELAC 1-LOOP + CutTools + OneLoop
- Real corrections: HELAC-DIPOLES (Catani Seymour & Nagy Soper schemes)

Functionality extended to produce NTuple → scale variations, PDF errors, ...

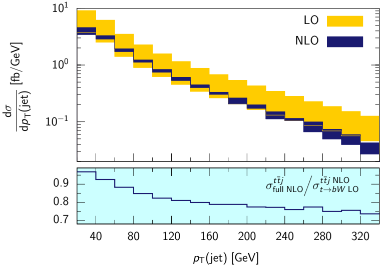
$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$: NWA

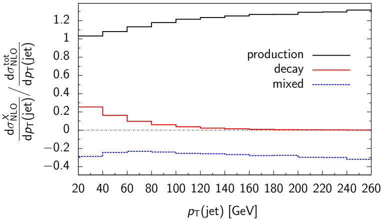
Melnikov, Schulze, Scharf '12

Inclusive $\sigma_{\rm NLO}(t\bar{t}j)$ in NWA → convolution of $\sigma(t\bar{t}+nj)$ and $\Gamma(t\bar{t}+nj)$, $n \leq 2$.
Expansion up to $\mathcal{O}(\alpha_s^4)$

$$\begin{aligned}
\mathrm{d}\sigma^{\rm NLO}_{t\bar{t}+1j} = \Gamma^{-2}_{t,\rm tot}\Big(&\mathrm{d}\sigma^{\rm LO}_{t\bar{t}+1j}\mathrm{d}\Gamma^{\rm LO}_{t\bar{t}} + \mathrm{d}\sigma^{\rm LO}_{t\bar{t}}\mathrm{d}\Gamma^{\rm LO}_{t\bar{t}+1j} \\
&+ \left(\mathrm{d}\sigma^{\rm virt}_{t\bar{t}+1j} + \mathrm{d}\sigma^{\rm real}_{t\bar{t}+2j}\right)\mathrm{d}\Gamma^{\rm LO}_{t\bar{t}} + \mathrm{d}\sigma^{\rm LO}_{t\bar{t}}\left(\mathrm{d}\Gamma^{\rm virt}_{t\bar{t}+1j} + \mathrm{d}\Gamma^{\rm real}_{t\bar{t}+2j}\right) \\
&+ \mathrm{d}\sigma^{\rm real}_{t\bar{t}+1j}\mathrm{d}\Gamma^{\rm real}_{t\bar{t}+1j} + \mathrm{d}\sigma^{\rm virt}_{t\bar{t}}\mathrm{d}\Gamma^{\rm LO}_{t\bar{t}+1j} + \mathrm{d}\sigma^{\rm LO}_{t\bar{t}+1j}\mathrm{d}\Gamma^{\rm virt}_{t\bar{t}}\Big)
\end{aligned}$$

$$\text{LHC 7 TeV}: \quad \sigma_{\rm NLO} = 323\ (\mathrm{Pr}) + \underbrace{40.5\ (\mathrm{Dec})}_{14\%} - \underbrace{75.5\ (\mathrm{Mix})}_{26\%} = 288\ \mathrm{fb}.$$





Setup for LHC 13 TeV

- Different lepton families: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$
  $\Rightarrow \gamma^* \to \ell^\pm\ell^\mp$ interference neglected (0.1% at LO)
- All light quarks (including bottom) and leptons are massless
- Contribution from initial state b-quarks are neglected ($<$ 1% at LO)
- Top quark: $m_t = 173.2$ GeV
- Final states: exactly 2 b jets, at least 1 light jet,
  2 charged leptons and missing E_T
- Jets: partons with $|\eta| < 5$, anti-k_T with $\Delta R = 0.5$
- Cuts:

$$
\begin{aligned}
&p_{T\ell} > 30\ \mathrm{GeV}\,, && p_{Tj} > 40\ \mathrm{GeV}\,,\\
&p_T^{\mathrm{miss}} > 40\ \mathrm{GeV}\,, && \Delta R_{jj} > 0.5\,,\\
&\Delta R_{\ell\ell} > 0.4\,, && \Delta R_{\ell j} > 0.4\,,\\
&|y_\ell| < 2.5\,, && |y_j| < 2.5\,.
\end{aligned}
$$

Total Cross Section

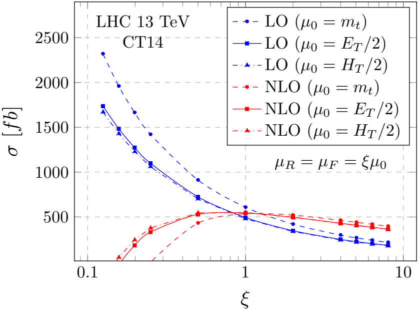
PDF: CT14

Fixed scale: $\mu_0 = m_t$

Dynamical scale: $\mu_0 = E_T/2$ and $H_T/2$

$$E_T = \sqrt{m_t^2 + p_T^2(t)} + \sqrt{m_t^2 + p_T^2(\bar{t})}$$

$$H_T = \sum_i p_T(i) + p_T^{\rm miss}, \quad i = e^+, \mu^-, b, \bar{b}, j_1.$$

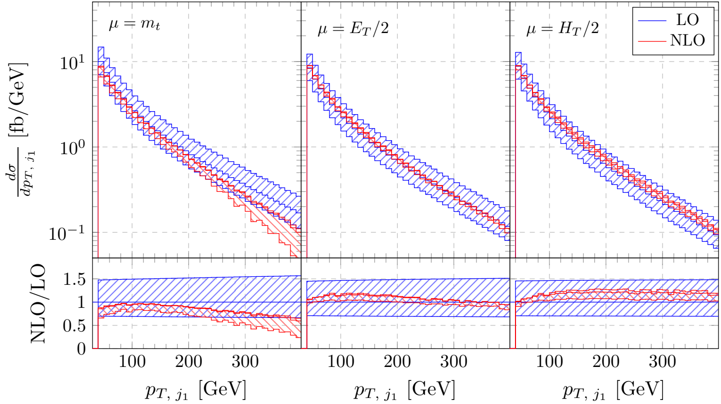


μ_0	$\sigma_{\rm LO}[fb]$	$\sigma_{\rm NLO}[fb]$	$\mathcal{K}$
m_t	$608.09\,^{+50\%}_{-31\%}$(scale)	$537.24\,^{+2\%}_{-20\%}$(scale) $^{+3\%}_{-3\%}$(pdf)	0.88
$E_T/2$	$493.54\,^{+47\%}_{-30\%}$(scale)	$544.64\,^{+1\%}_{-9\%}$(scale) $^{+3\%}_{-3\%}$(pdf)	1.10
$H_T/2$	$479.38\,^{+46\%}_{-30\%}$(scale)	$538.66\,^{+1\%}_{-9\%}$(scale) $^{+3\%}_{-3\%}$(pdf)	1.12

[Bevilacqua, HBH, Kraus, Worek '16]

Differential Distributions (1)

Transverse momentum of the hardest light jet



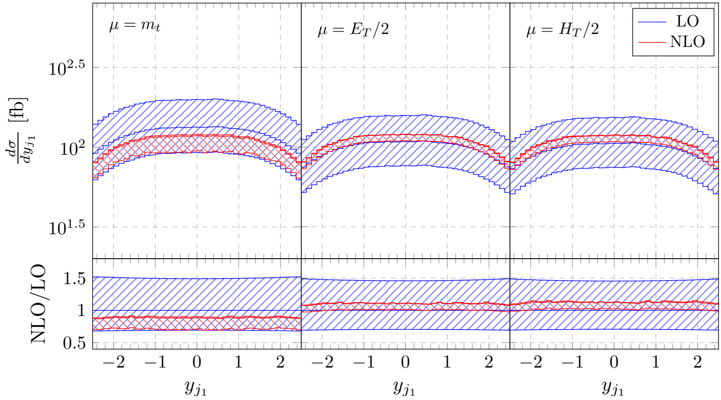
Scale uncertainty:

$$\left(\frac{\mu_R}{\mu_0}, \frac{\mu_F}{\mu_0}\right) = \Big\{(0.5, 0.5), (0.5, 1), (1, 0.5), (1, 1), (1, 2), (2, 1), (2, 2)\Big\}$$

[Bevilacqua, HBH, Kraus, Worek '16]

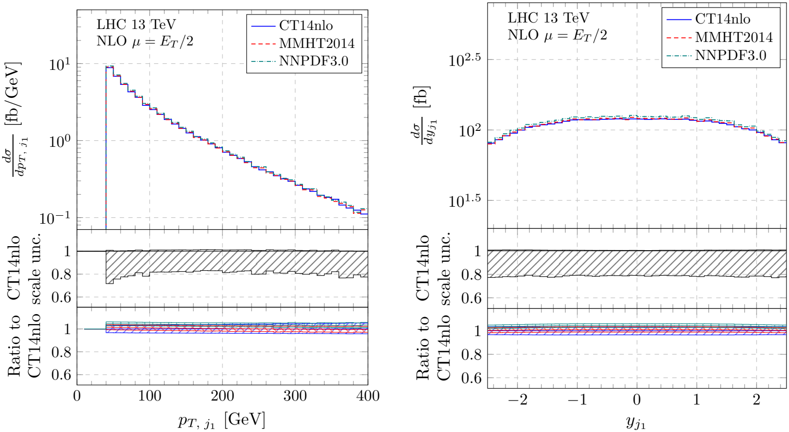
Differential Distributions (2)

Rapidity of the hardest light jet



[Bevilacqua, HBH, Kraus, Worek '16]

PDF Uncertainties

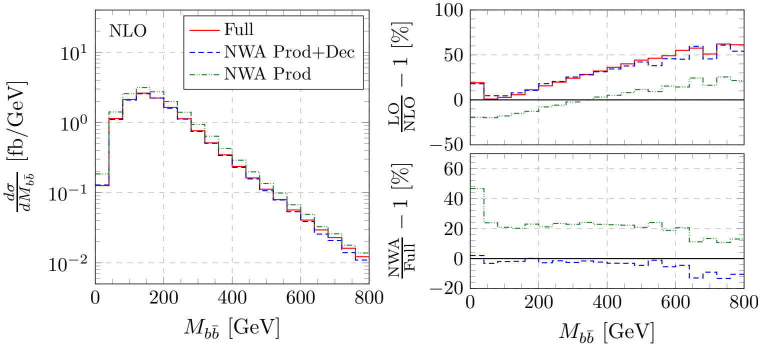


[Bevilacqua, HBH, Kraus, Worek '16]

Comparison with NWA (1)

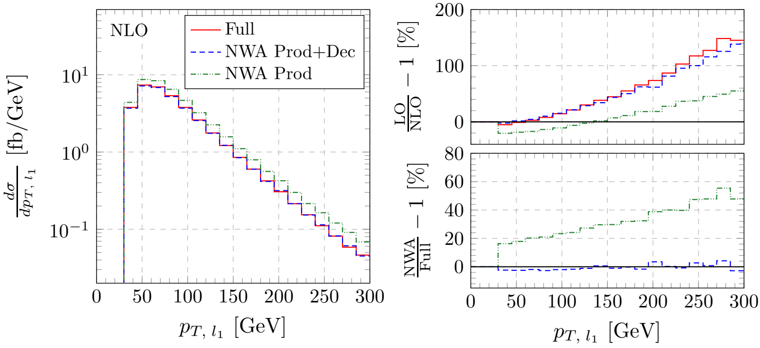
- $\mu_R = \mu_F = m_t$, CT14 PDF.
- NWA Prod $\rightarrow$ NLO corrections only in production.

$$\sigma^{\rm Full}_{\rm NLO} = 537\ {\rm fb}, \quad \sigma^{\rm NWA(Prod+Dec)}_{\rm NLO} = 527\ {\rm fb}, \quad \sigma^{\rm NWA(Prod)}_{\rm NLO} = 656\ {\rm fb}.$$



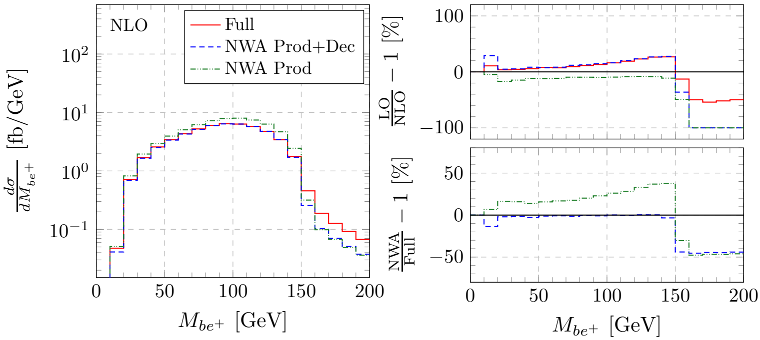
[Bevilacqua, HBH, Kraus, Schulze, Worek, in preparation]

Comparison with NWA (2)



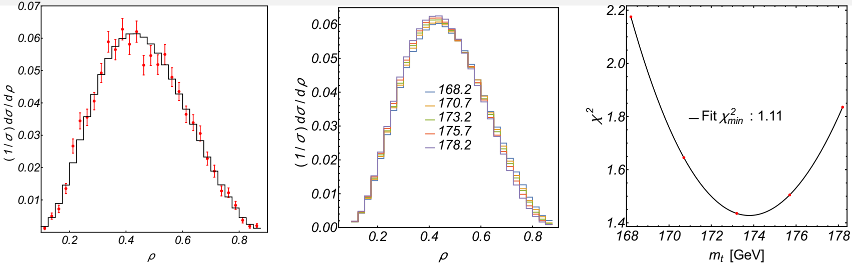
[Bevilacqua, HBH, Kraus, Schulze, Worek, in preparation]

Comparison with NWA (3)



[Bevilacqua, HBH, Kraus, Schulze, Worek, in preparation]

m_{top} fit

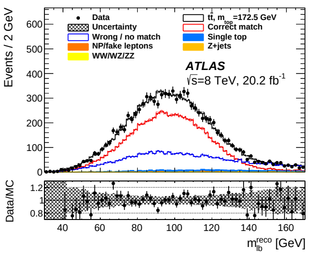


- Pseudodata sets are generated using $m_t^{\text{in}} = 173.2$ GeV
  $\rightarrow$ NLO off-shell, with $\mu_0 = H_T/2$, luminosity of 25 fb^{-1}
- Fit with theory templates gives m_t^{out}
- Templates: $m_t = [168.2, 170.7, 173.2, 175.7, 178.2]$ GeV
  - NLO off-shell: $\mu_0 = \{m_t, E_T/2, H_T/2\}$
  - NLO NWA: $\mu_0 = m_t$
  - NLO NWA_{Prod}: $\mu_0 = m_t$
- Observables: M_{be^+} and $\mathcal{R}(m_t, \rho_s)$ for the moment
- Analysis are carried out at fixed order, no parton shower involved

Observable (1): M_{be^+}

Well studied observable for $t\bar{t}$

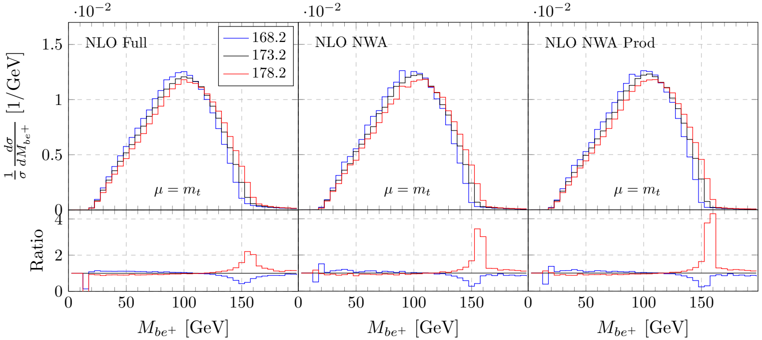
- b-jet fragmentation
- off-shell QCD effects
- off-shell QCD+EW effects
- top-quark mass extraction



m_t = 172.99±0.41(stat)±0.74(syst) GeV [ATLAS'16]

m_t = 172.22±0.18(stat)$^{+0.89}_{-0.93}$(sys) GeV [CMS'17]

M_{be^+} from $t\bar{t}j$



Result (1): M_{be^+}

PRELIMINARY

Theory Template	$m_t^{\rm out} \pm \Delta m_t^{\rm out}$	$m_t^{\rm in} - m_t^{\rm out}$
Full NLO, $\mu = H_T/2$	173.18 ± 0.15	+0.02
Full NLO, $\mu = E_T/2$	173.23 ± 0.15	-0.03
Full NLO, $\mu = m_t$	173.22 ± 0.16	-0.02
NWA NLO, $\mu = m_t$	173.98 ± 0.16	-0.78
NWA NLO$_{\rm Pr}$, $\mu = m_t$	172.62 ± 0.17	+0.58

- NWA vs Off-shell: shift of +760 MeV
- NWA vs NWA$_{\rm Prod}$: shift of -1.36 GeV
- shifts due to scale variation: $H_T/2$ and $E_T/2 \to \mathcal{O}(50\ \rm MeV)$
  $m_t \to \mathcal{O}(1\ \rm GeV)$
- different PDF sets shift m_t by $\mathcal{O}(30\ \rm MeV)$

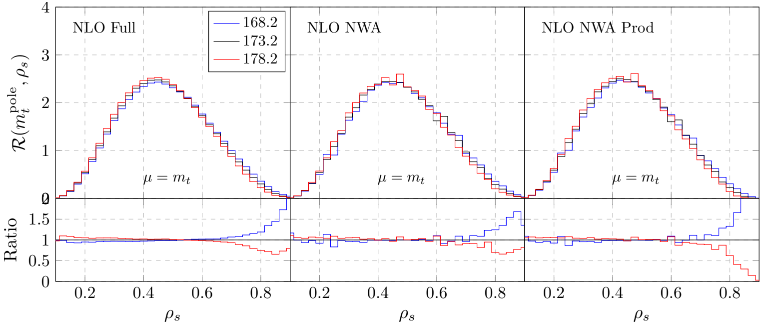
[Bevilacqua, HBH, Kraus, Schulze, Worek, in preparation]

Observable (2): $\mathcal{R}(m_t, \rho_s)$

- Alternative method to m_t extraction [Alioli, Fernandez, Fuster, Irles, Moch, Uwer, Vos 13]

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1-\text{jet}}} \frac{d\sigma_{t\bar{t}+1-\text{jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s), \qquad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1-\text{jet}}}}$$

- 7 TeV: $m_t = 173.7 \pm 2.2$ GeV [ATLAS'15]
- 8 TeV: $m_t = 169.9 \pm 3.9$ GeV [CMS'16]



Result (2): $\mathcal{R}(m_t, \rho_s)$

PRELIMINARY

Theory Template	$m_t^{\rm out} \pm \Delta m_t^{\rm out}$	$m_t^{\rm in} - m_t^{\rm out}$
Full NLO, $\mu = H_T/2$	173.09 $\pm$ 0.42	+0.11
Full NLO, $\mu = E_T/2$	172.45 $\pm$ 0.39	+0.75
Full NLO, $\mu = m_t$	173.76 $\pm$ 0.40	-0.56
NWA NLO, $\mu = m_t$	175.65 $\pm$ 0.31	-2.45
NWA NLO$_{\rm Pr}$, $\mu = m_t$	169.59 $\pm$ 0.30	+3.61

- NWA vs Off-shell: shift of $+1.89$ GeV
- NWA vs NWA$_{\rm Prod}$: shift of -6.06 GeV
- shifts due to scale variation: $H_T/2$ and $E_T/2 \to 0.6 - 1.2$ GeV
$m_t \to 2.1 - 2.8$ GeV
- different PDF sets shift m_t by $0.4 - 0.7$ GeV

[Bevilacqua, HBH, Kraus, Schulze, Worek, in preparation]

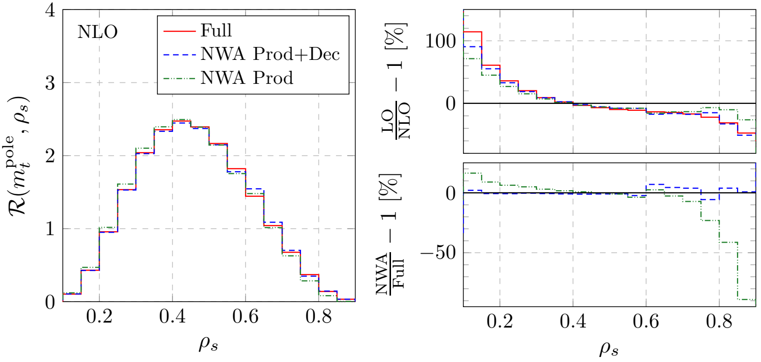
Conclusion

- ✓ Complete description for $t\bar{t}j$ process with resonant and non-resonant contributions at NLO QCD.
- ✓ Different scales have been studied: m_t, $E_T/2$ and $H_T/2$
- ✓ Scale and PDF uncertainties for total cross section and differential distributions
- ✓ Comparison with NWA calculation for total cross section and differential distributions
  $\Rightarrow$ NLO corrections to decay important
- ✓ Preliminary results for top quark mass extraction from M_{b,e^+} and $\mathcal{R}(m_t, \rho)$
  $\Rightarrow$ Fixed scale $\mu_{R,F}$ not suitable for top mass extraction $d\sigma/dX$
- $\Rightarrow$ More observables to study: $M_{t\bar{t}}$, $M_{\ell\ell}$, H_T

BACKUPs

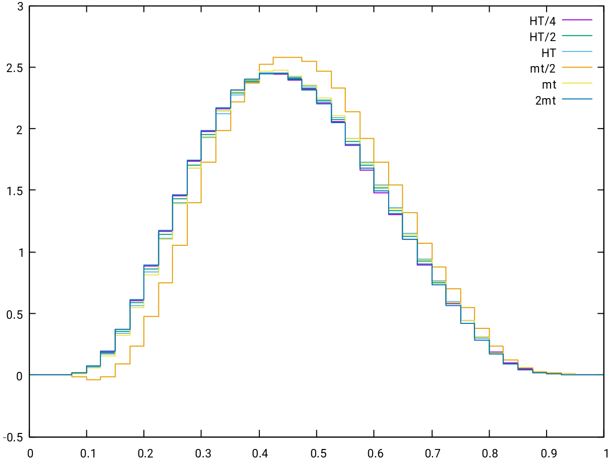
Comparison with NWA (4)

$$\mathcal{R}(m_t^{\rm pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1-{\rm jet}}} \frac{d\sigma_{t\bar{t}+1-{\rm jet}}}{d\rho_s}(m_t^{\rm pole}, \rho_s), \qquad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1-{\rm jet}}}}$$

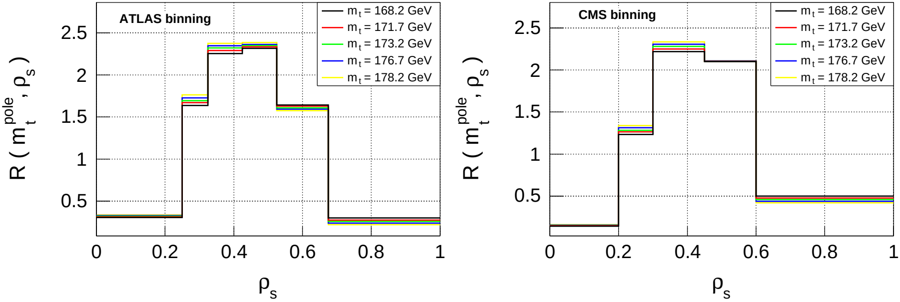


[Bevilacqua, HBH, Kraus, Schulze, Worek, in preparation]

Scale dependence of ρ distributions



ρ distributions: ATLAS and CMS binning



m_t from $\mathcal{R}(m_t, \rho_s)$: ATLAS binning

Theory Template	$m_t^{\rm out} \pm \Delta m_t^{\rm out}$	$m_t^{\rm in} - m_t^{\rm out}$
Full NLO, $\mu = H_T/2$	173.05 ± 1.31	+0.15
Full NLO, $\mu = E_T/2$	172.19 ± 1.34	+1.01
Full NLO, $\mu = m_t$	173.86 ± 1.39	-0.66
NWA NLO, $\mu = m_t$	175.22 ± 1.15	-2.02
NWA $\text{NLO}_{\rm Pr}$, $\mu = m_t$	169.39 ± 1.46	+3.81

- NWA vs Off-shell: shift of +1.36 GeV
- NWA vs $\text{NWA}_{\rm Prod}$: shift of -5.83 GeV

m_t from $\mathcal{R}(m_t, \rho_s)$: CMS binning

Theory Template	$m_t^{\rm out} \pm \Delta m_t^{\rm out}$	$m_t^{\rm in} - m_t^{\rm out}$
Full NLO, $\mu = H_T/2$	173.09 ± 1.53	+0.11
Full NLO, $\mu = E_T/2$	172.20 ± 1.54	+1.00
Full NLO, $\mu = m_t$	173.94 ± 1.49	-0.74
NWA NLO, $\mu = m_t$	175.66 ± 1.10	-2.46
NWA $\mathrm{NLO_{Pr}}$, $\mu = m_t$	169.96 ± 1.80	+3.24

- NWA vs Off-shell: shift of +1.72 GeV
- NWA vs $\mathrm{NWA_{Prod}}$: shift of -5.7 GeV