Top Quark Pair Production with a Jet with NLO QCD Off-Shell Effects

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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:

- Motivation
  - ⇒ $t\bar{t}j$ production at the LHC
  - ⇒ top-quark off-shell effects (based on $t\bar{t}$ studies)
- Complete off-shell effects with HELAC-NLO for $t\bar{t}j$
- Results for LHC at 8 & 13 TeV
- Summary & Outlook

$t\bar{t}j$ 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?

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

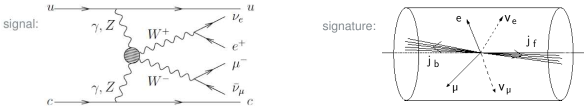
$$\sigma(t\bar{t}) = 807 \text{ pb}$$

TOP++; Czakon, Mitov '14

Jet p_T cut [GeV]	$\sigma(t\bar{t}j)$ [pb]	$\sigma(t\bar{t}j)/\sigma(t\bar{t})$ [%]
40	296.97 $\pm$ 0.29	37
60	207.88 $\pm$ 0.19	26
80	152.89 $\pm$ 0.13	19
100	115.60 $\pm$ 0.14	14
120	89.05 $\pm$ 0.10	11

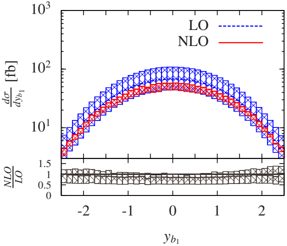
$t\bar{t}j$ as background

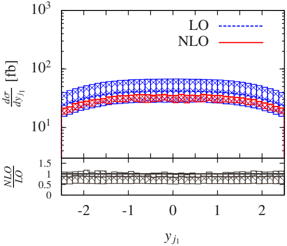
- Background for SM Higgs production in VBF: $qq \to Hqq \to WWqq$



- 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

Theoretical Predictions for $t\bar{t}j$ production

✓ NLO QCD corrections to on-shell $t\bar{t}j$ production

Dittmaier, Uwer, Weinzierl '07 '09

✓ NLO QCD corrections to on-shell $t\bar{t}j$ production with LO decay

Melnikov, Schulze '10

✓ NLO QCD corrections to $t\bar{t}j$ in NWA (corrections in production & decay)

Melnikov, Schulze, Scharf '12

✓ NLO QCD corrections to $t\bar{t}j$ with full top-quark and W off-shell effects

Bevilacqua, HBH, Kraus, Worek '16

✓ NLO QCD correction to on-shell $t\bar{t}j$ production + PS

- PowHel + PYTHIA, no spin correlations

  Kardos, Papadopoulos, Trocsanyi '11
- POWHEG + PYTHIA/HERWIG, with spin correlations at LO

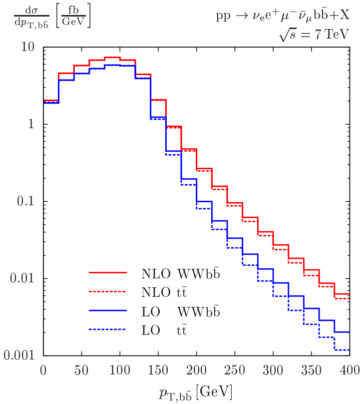
  Alioli, Moch, Uwer '12
- Helac-NLO + Deductor, without top-quark decays

  Czakon, HBH, Kraus, Worek '15

Off-shell effects for $t\bar{t}$ (1)

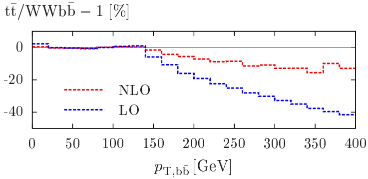
Contributions neglected in the NWA (off-shell effects) are expected to be suppressed by powers of $\Gamma_t/m_t \sim 1\%$.

- true for (sufficiently) inclusive observables
- could be much larger for differential distributions



Full NWA ($t\bar{t}$) vs full calculation ($WWb\bar{b}$)

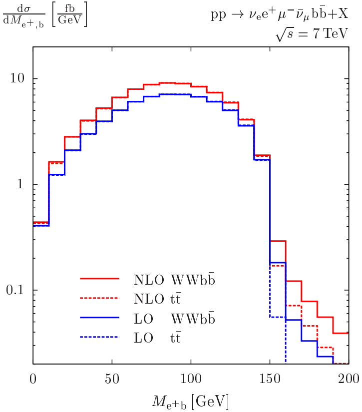
A. Denner et al. '11, '12, '15
G. Bevilacqua et al. '11, '16
R. Frederix '14
F. Cascioli et al. '14
G. Heinrich et al '14



Denner, Dittmaier, Kallweit, Pozzorini, Schulze '12

Off-shell effects for $t\bar{t}$ (2)

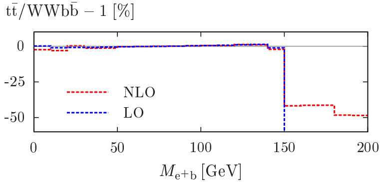
- Full NWA ($t\bar{t}$) vs full calculation ($WWb\bar{b}$) for M_{e^+b}



- If both top and W decay on-shell
  $\to$ end-point given by sharp cut

$$M_{\ell b} = \sqrt{m_t^2 - m_W^2} \approx 152 \text{ GeV}$$

- Additional radiation & off-shell effects introduce smearing

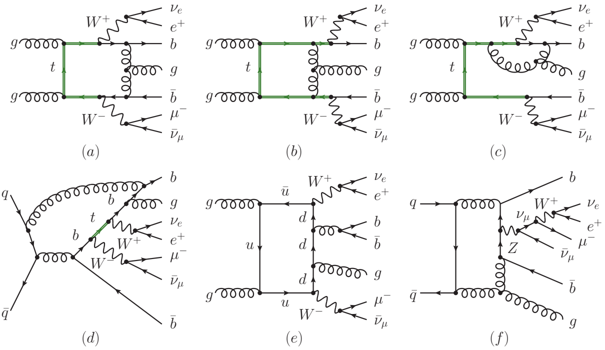


Denner, Dittmaier, Kallweit, Pozzorini, Schulze '12

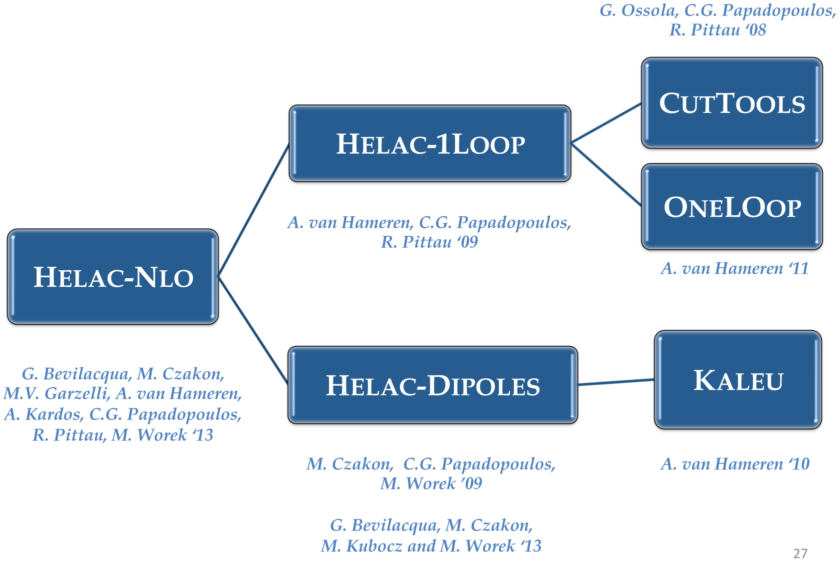
m_t measurement based on $M_{\ell b}$ $\to$ extracted m_t is sensitive to theory template (LO/NLO and Full/NWA). *Heinrich, Maier, Nisius, Schlenk, Winter '14*

Off-shell effects for $t\bar{t}j$

- $t\bar{t}j$ production at NLO QCD with tops decay leptonically $\mathcal{O}(\alpha_s^4\alpha^4)$
- Diagrams with complete off-shell effects for top-quark and W boson for gg initial state:
  - LO: 508
  - Real: 4447
  - Virtual: 39180 $\rightarrow$ 1155 hexagons and 120 heptagons



Helac-NLO


G. Ossola, C.G. Papadopoulos, R. Pittau '08
CUTTOOLS
HELAC-1LOOP
ONELOOP
A. van Hameren, C.G. Papadopoulos, R. Pittau '09
A. van Hameren '11
HELAC-NLO
KALEU
HELAC-DIPOLES
G. Bevilacqua, M. Czakon, M.V. Garzelli, A. van Hameren, A. Kardos, C.G. Papadopoulos, R. Pittau, M. Worek '13
M. Czakon, C.G. Papadopoulos, M. Worek '09
A. van Hameren '10
G. Bevilacqua, M. Czakon, M. Kubocz and M. Worek '13
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Helac-NLO

- HELAC-1LOOP → automatic evaluation of loop numerators
- CutTools → Ossola-Papadopoulos-Pittau (OPP) reduction technique
- OneLOop → evaluation of scalar integrals with complex masses

- HELAC-DIPOLES → The singularities from soft or collinear parton emissions isolated via subtraction methods for NLO QCD
  - Catani-Seymour dipoles subtraction
  - Nagy-Soper subtraction scheme
  - Both for massive and massless cases

- KALEU → phase space integration
  - Multi-channel Monte Carlo techniques
  - Adaptive weight optimization
  - Dedicated additional channels for each subtraction term for both subtraction schemes

Setup for LHC 8 TeV

- SM parameters:

$$G_\mathrm{F} = 1.16637 \cdot 10^{-5}\ \mathrm{GeV}^{-2}\,, \quad m_\mathrm{t} = 173.3\ \mathrm{GeV}\,,$$
$$m_\mathrm{W} = 80.399\ \mathrm{GeV}\,, \quad \Gamma_\mathrm{W} = 2.09974\ \mathrm{GeV}\,,$$
$$m_\mathrm{Z} = 91.1876\ \mathrm{GeV}\,, \quad \Gamma_\mathrm{Z} = 2.50966\ \mathrm{GeV}\,,$$
$$\Gamma_\mathrm{t}^\mathrm{LO} = 1.48132\ \mathrm{GeV}\,, \quad \Gamma_\mathrm{t}^\mathrm{NLO} = 1.3542\ \mathrm{GeV}\,.$$

- MSTW2008 NLO PDF, $\mu_R = \mu_F = \mu_0 = m_t$.
- All light quarks (including bottom) and leptons are massless
- Contribution from initial state b-quarks are neglected (0.8% at LO)
- Jets: partons with $|\eta| < 5$, anti-k_T with $\Delta R = 0.5$
- Final states: exactly 2 b jets, at least 1 light jet, 2 charged leptons and missing E_T
- Cuts:

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

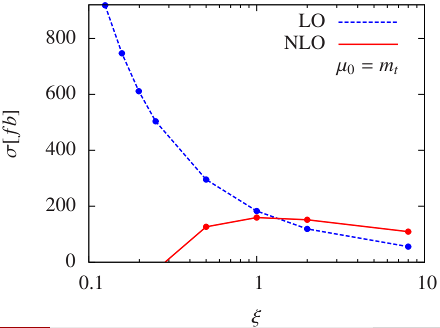
Total cross section

For LHC at 8 TeV:

$$\sigma^{\rm LO} = 183.1\,^{+112.2\,(61\%)}_{-64.2\,(35\%)}\ {\rm fb} \quad \sigma^{\rm NLO} = 159.7\,^{-33.1\,(21\%)}_{-7.9\,(\ \ 5\%)}\ {\rm fb}$$

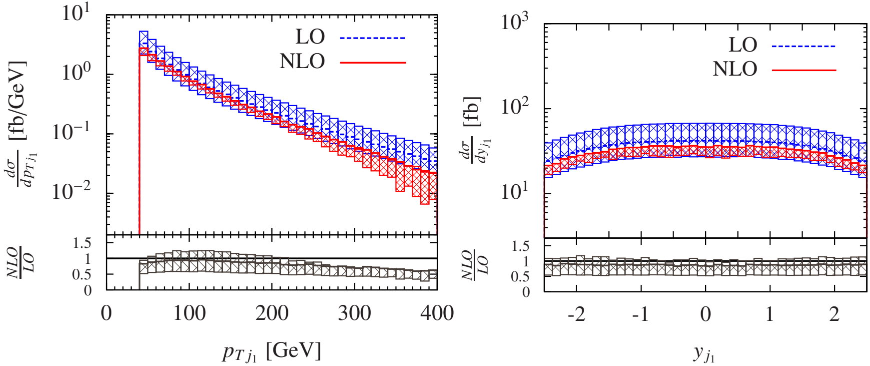
- NLO corrections → -13 % at $\mu = m_t$
- Reduced scale dependence from LO to NLO

Scale dependence, $\mu_R = \mu_F = \xi m_t$



Differential distributions (1)

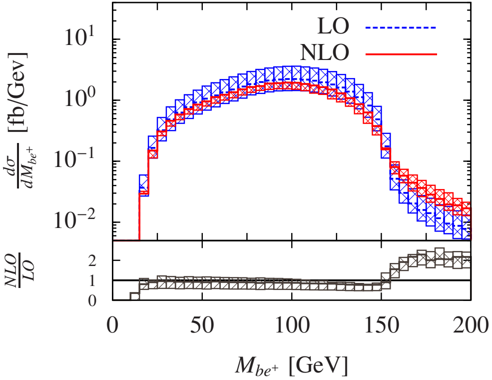
Transverse momentum and rapidity of the hardest light jet



- Scale dependence band: $\{0.5m_t, m_t, 2m_t\}$
- Shape distortion on $p_T(j_1)$ distribution.
  Stable K-factor $\rightarrow$ properly chosen dynamical scale
- $y(j_1)$ receives contributions from various scales

Differential distributions (2)

⇒ (be^+) pair that returns the smallest invariant mass



- If both top and W decay on-shell, end-point given by sharp cut
- Addition radiation and off-shell effects introduce smearing
- Highly sensitive to the details of the description of the process

$$M_{be^+}^{max} = \sqrt{m_t^2 - m_W^2} \simeq 153.3 \text{ GeV}$$

Results for LHC at 13 TeV (to appear)

More comprehensive study on off-shell $t\bar{t}j$ production

- Fixed vs dynamical scale, μ_R and μ_F variations
- PDF uncertainties (different PDF choice, variation on internal sets)

$\Rightarrow$ highly time consuming and CPU intensive

$\Rightarrow$ Extend Helac-NLO functionality to produce NTuple

Fixed scale: $\mu_0 = m_t$

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

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

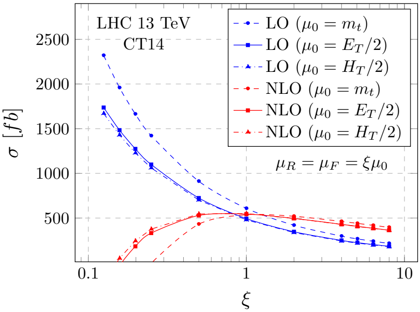
$$H_T = \sum_i p_T(i), \qquad i = e^+, \mu^-, \nu, b, \bar{b}, j_1.$$

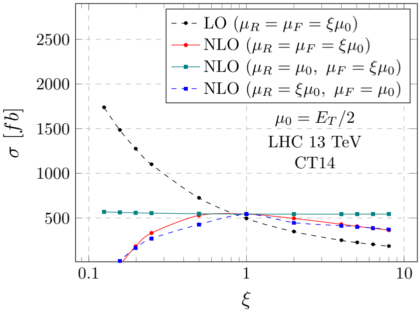
PDFset: CT14, MMHT2014, NNPDF3.0.

Scale uncertainty calculated from the envelope of the following:

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

Fixed vs dynamical scale (1)

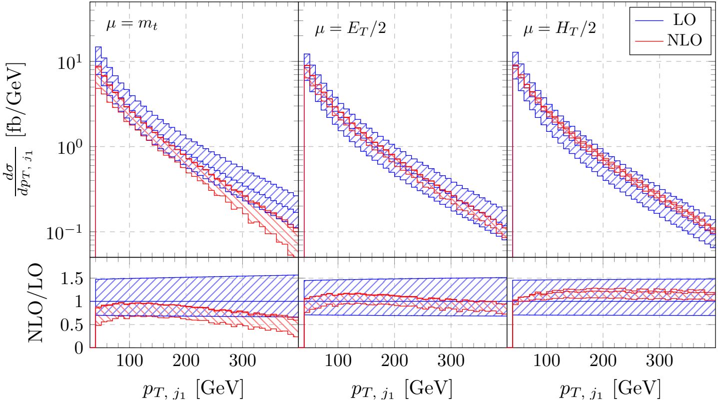




μ_0	σ_{LO} [fb]	σ_{NLO} [fb]
m_t	$608.09^{+50\%}_{-31\%}$	$537.24^{+2\%}_{-35\%}$
$E_T/2$	$493.54^{+47\%}_{-30\%}$	$544.64^{+1\%}_{-22\%}$
$H_T/2$	$479.38^{+46\%}_{-30\%}$	$549.65^{+2\%}_{-10\%}$

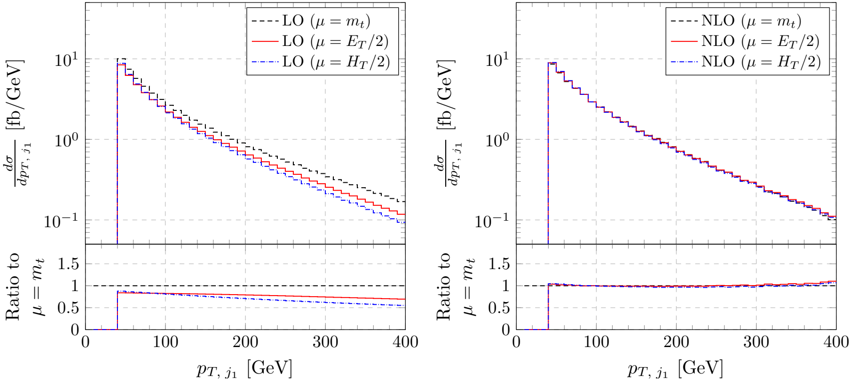
Fixed vs dynamical scale (2)

Transverse momentum of the hardest light jet



Fixed vs dynamical scale (3)

Transverse momentum of the hardest light jet

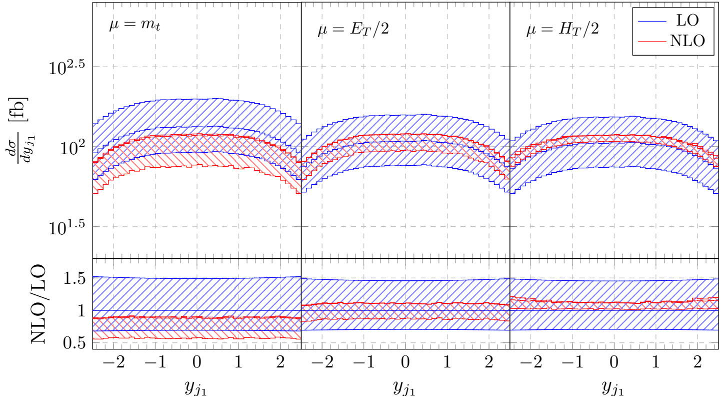


LO ratio

NLO ratio

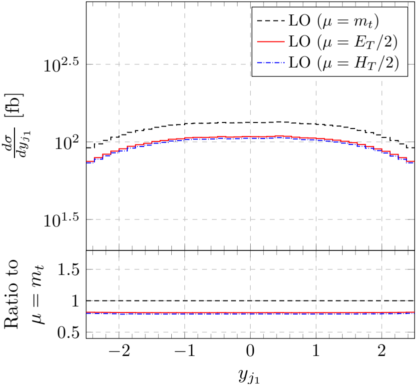
Fixed vs dynamical scale (4)

Rapidity of the hardest light jet

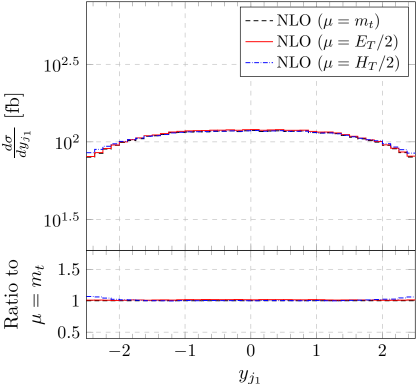


Fixed vs dynamical scale (5)

Rapidity of the hardest light jet



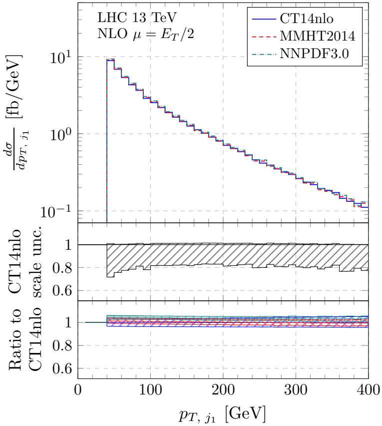
LO ratio

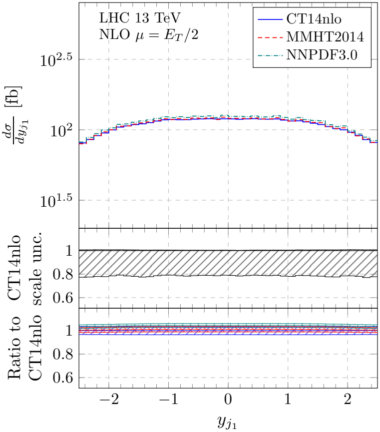


NLO ratio

PDF uncertainties

PDF uncertainties on the total cross section $\sim 2 - 4$ %.



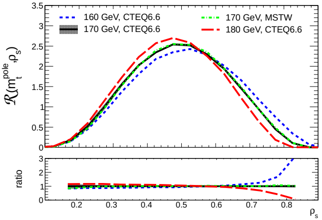


Summary

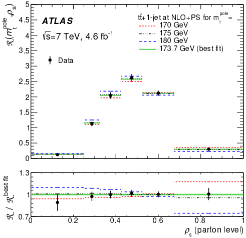
Summary & Outlook

- ✓ Complete description for $t\bar{t}j$ process with resonant and non-resonant contributions at NLO QCD.
- ✓ Produce NTuple from Helac-NLO → more feasible to study PDF uncertainties and different scale choice, more flexible analysis.
- ✗ Study bottom-mass effects: 5FS vs 4FS
- ✗ Dedicated comparison to NWA calculation *Melnikov, Schulze, Scharf '11*
- ✗ Top-mass measurement

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



Alioli, etal., arXiv:1303.6415 [hep-ph]



ATLAS, arXiv:1507.01769 [hep-ex]