Research Training Group Physics of the Heaviest Particles at the LHC | RWTH AACHEN UNIVERSITY

Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Complete NLO corrections to off-shell $t\bar{t}$ production in the $\ell + j$ channel

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P3H

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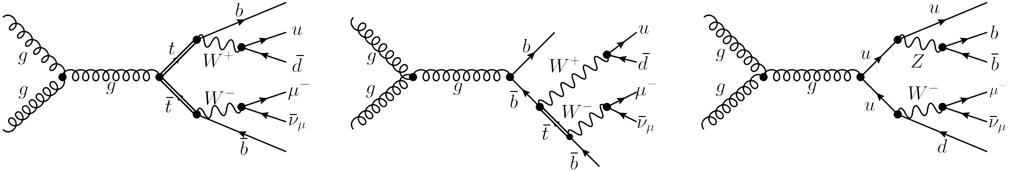
Motivation for $t\bar{t} \to \ell + \text{jets}$ with NLO QCD+EW corrections

- ℓ+jets is one of the *highest-statistics* decay mode (BR $\sim 30\%$, of all $t\bar{t}$ events, excluding τ) $\Rightarrow$ key channel for precision differential measurements.
- Precise theory templates reduce the dominant systematic in top-quark mass fits; off-shell effects especially important to model top mass effects, current theory uncertainty $\delta m_t \sim 0.3\,\text{GeV}$ (ATLAS, Phys.Lett.B 867 (2025) 139608).
- Electroweak Sudakov logarithms can give $\mathcal{O}(-10\%)$ corrections in the boosted regime, crucial for new-physics searches (Czakon et al., JHEP 10 (2017) 186).



(Feynman diagrams done with FeynGame, Bündgen et al., Comput.Phys.Commun. 314 (2025) 109662)

Current Theoretical Status of $t\bar{t}$ + Decays

Di-leptonic channel $(\ell^+\ell'^- + 2\nu + b\bar{b})$

- NLO QCD: (Bevilacqua et al., JHEP 02 (2011) 083), (Denner et al., Phys. Rev. Lett. 106 (2011) 052001), (Heinrich et al., JHEP 06 (2014) 158).
- NLO EW: (Denner & Pellen, JHEP 08 (2016) 155).
- NNLO QCD (NWA): (Czakon, Mitov, Poncelet, JHEP 05 (2021) 212), (Mazzitelli et al., PRL 127 (2021) 062001).

Semi-leptonic channel $(\ell + \nu + 2j + b\bar{b})$

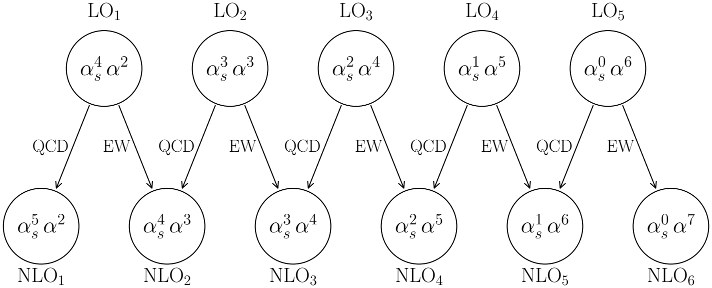
- NLO QCD: (Denner & Pellen, JHEP 02 (2018) 013).
- **This work**: first complete NLO QCD & EW corrections including all Born channels.

Focus so far has been on the **di-leptonic** channel; the **semi-leptonic** mode is now catching up.

Born-level Contributions to $pp \to \mu^- \bar{\nu}_\mu b\bar{b}jj$

LO$_1$: $\mathcal{O}(\alpha_s^4\alpha^2)$
QCD-dominated; no doubly-resonant $t\bar{t}$.

LO$_2$: $\mathcal{O}(\alpha_s^3\alpha^3)$
Photon-initiated; suppressed by photon PDFs, also via interference.

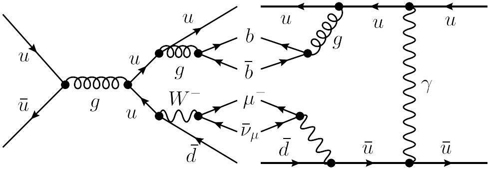


LO$_3$: $\mathcal{O}(\alpha_s^2\alpha^4)$
Dominant; includes doubly-resonant $t\bar{t}$.

LO$_4$: $\mathcal{O}(\alpha_s\alpha^5)$
Photon initiated or via interference, includes doubly-resonant $t\bar{t}$.

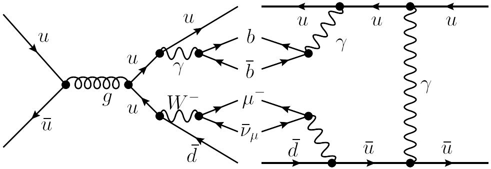
LO$_5$: $\mathcal{O}(\alpha^6)$
Pure EW; no gluons but includes doubly-resonant $t\bar{t}$.

Born-level Contributions to $pp \to \mu^- \bar{\nu}_\mu b\bar{b}jj$



Left diagram: LO_1 Right diagram: LO_3

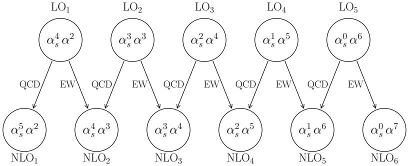
Interference $\Rightarrow$ $\mathbf{LO}_2$



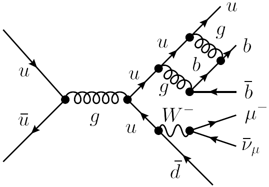
Left diagram: LO_3 Right diagram: LO_5

Interference $\Rightarrow$ $\mathbf{LO}_4$

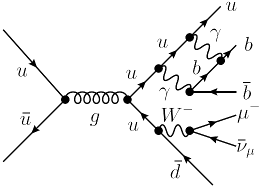
- Include all resonant and non-resonant diagrams
- Photons and b-quarks in the initial state
- All possible light-jet flavors, not just W decays like $u\bar{d}$ or $c\bar{s}$ $\Rightarrow$ 56 channels at Born-level after pdf-summation



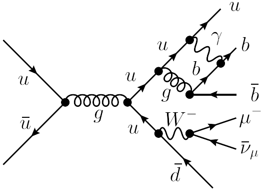
Loop Contributions and Real Radiation



QCD loops

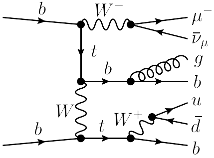


EW loops

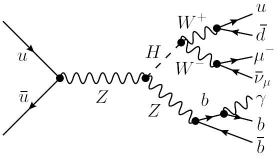


Mixed loops

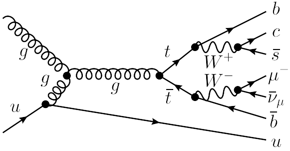
$\Rightarrow$ include EW corrections for consistency



NLO gluon radiation



NLO photon radiation

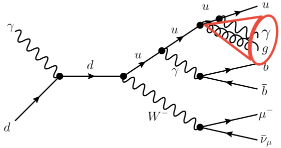


init./final state splitting

Democratic Clustering for $pp \to \mu^- \bar{\nu}_\mu b\bar{b}jj$

- **NLO photon radiation** for example in $d\gamma \to \mu^- \bar{\nu}_\mu b\bar{b}ug\gamma$
- Photons and jets together in final state $\Rightarrow$ **Democratic clustering** (Glover et al., Z. Phys. C 62, 311–321 (1994))
- To exclude soft gluons, jet algorithm clusters photon-parton pair to either jet or photon depending on energy fraction
- **Photon energy fraction in jet:**

$$z_\gamma = \frac{E_\gamma}{E_\gamma + E_{\text{jet}}}$$



- If $z_\gamma > z_{\gamma,\text{cut}}$, classify cluster as **photon** $\Rightarrow$ cut event
- If $z_\gamma < z_{\gamma,\text{cut}}$, classify cluster as **jet** $\Rightarrow$ keep event
- Cut destroys IR-safety by restricting collinear photon phase space $\Rightarrow$ needs to be **restored with fragmentation function**

Fragmentation Function and Collinear Divergence Cancellation

$$d\hat{\sigma}_{\text{jet}+\gamma} = d\hat{\sigma}^{\text{demo}}_{\text{jet}+\gamma} - \sum_j d\hat{\sigma}^{\text{Born}}_j \otimes D^B_{j\to\gamma}$$

- Collinear photon singularity is canceled by the **convolution of the Born-level cross section** with the bare fragmentation function (Gehrmann et al., JHEP 04 (2022) 031).

$$D^B_{q\to\gamma}(z) = D_{q\to\gamma}(z, \mu^2_{Fr}) - \frac{\alpha}{2\pi}\Gamma^{(0)}_{q\to\gamma}(z, \mu^2_{Fr}) + \mathcal{O}(\alpha^2)$$

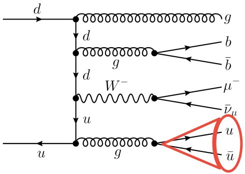
- The **bare fragmentation function** is split into:
  - a finite, non-perturbative part from experiment (ALEPH, Z.Phys.C 69 (1996) 365-378)
  - and a singular part (from factorization)
- μ_{Fr} dependence handled via **RG evolution**

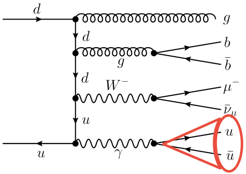
$$\Gamma^{(0)}_{q\to\gamma}(z, \mu^2_{Fr}) = -\frac{1}{\epsilon} Q_q^2 \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \left(\frac{\mu_R^2}{\mu_{Fr}^2}\right)^\epsilon P_{q\to\gamma}(z)$$

- $\Gamma^{(0)}$: **factorization kernel** with the DGLAP splitting function
- Cancels the collinear divergence from real photon emission

Photon-to-jet Conversion Function

- $\bar{u}d \to \mu^- \bar{\nu}_\mu b\bar{b}gu\bar{u}$ where $u\bar{u}$ can be collinear and clustered in a light jet can result from $\gamma \to q\bar{q}$ **splitting**.
- Underlying Born state $\bar{u}d \to \mu^- \bar{\nu}_\mu b\bar{b}g\gamma$ with **one-loop QED corrections** would cancel divergence, but this Born state is not part of our definition.
- **Introduce the photon-to-jet conversion function** to restore IR safety.





Photon-to-Jet Conversion and Divergence Cancellation

$$d\sigma_{X+q\bar{q}} = d\sigma^{\text{pert}}_{X+q\bar{q}} + d\sigma^{\text{LO}}_{X+\gamma} \int_0^1 dz\, D^B_{\gamma\to\text{jet}}(z)$$

- Collinear EW divergence from $\gamma \to q\bar{q}$ is canceled by the **convolution of the bare photon-to-jet conversion function** with the underlying Born process (Denner et al., Phys.Lett.B 798 (2019) 134951).

$$D^B_{\gamma\to\text{jet}}(z) = D_{\gamma\to\text{jet}}(z, \mu^2_{Fr}) - \frac{\alpha}{2\pi}\Gamma^{(0)}_{\gamma\to\text{jet}}(z, \mu^2_{Fr}) + \mathcal{O}(\alpha^2)$$

- The **bare conversion function** is split into:
  - a finite, non-perturbative part from experiment (Keshavarzi et al., Phys.Rev.D 97 (2018) 11, 114025)
  - and a singular part (from factorization)
- μ_{Fr} dependence handled via **RG evolution**

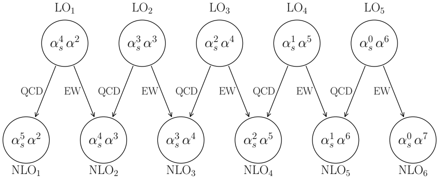
$$\Gamma^{(0)}_{\gamma\to\text{jet}}(z, \mu^2_{Fr}) = -\frac{1}{\epsilon} N_c \sum_q Q_q^2 \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \left(\frac{\mu_R^2}{\mu_{Fr}^2}\right)^\epsilon P_{\gamma\to\text{jet}}(z)$$

- $\Gamma^{(0)}$: **factorization kernel** includes sum over all light quark flavors, color factor N_c, and DGLAP splitting function.
- Cancels the collinear divergence from $\gamma \to q\bar{q}$ splitting.

Integrated Fiducial Cross-sections

(Mans, Stremmer, Worek, in preparation)

		σ_i [pb]	Ratio to Born_3
Born_1	$\mathcal{O}(\alpha_s^4\alpha^2)$	0.069(1)	0.44%
Born_2	$\mathcal{O}(\alpha_s^3\alpha^3)$	0.00012(5)	0.00%
Born_3	$\mathcal{O}(\alpha_s^2\alpha^4)$	15.632(2)	100.00%
Born_4	$\mathcal{O}(\alpha_s^1\alpha^5)$	0.06678(7)	0.43%
Born_5	$\mathcal{O}(\alpha_s^0\alpha^6)$	0.04839(5)	0.31%
NLO_1	$\mathcal{O}(\alpha_s^5\alpha^2)$	+ 0.072(2)	+ 0.46%
NLO_2	$\mathcal{O}(\alpha_s^4\alpha^3)$	− 0.0011(2)	− 0.01%
NLO_3	$\mathcal{O}(\alpha_s^3\alpha^4)$	− 0.95(1)	− 6.10%
NLO_4	$\mathcal{O}(\alpha_s^2\alpha^5)$	+ 0.056(1)	+ 0.36%
NLO_5	$\mathcal{O}(\alpha_s^1\alpha^6)$	+ 0.0932(3)	+ 0.60%
NLO_6	$\mathcal{O}(\alpha_s^0\alpha^7)$	+ 0.001142(9)	+ 0.01%
LO		$13.6207(9)^{+30.7\%}_{-22.0\%}$	0.871
Born		$15.817(2)^{+30.7\%}_{-22.0\%}$	1.012
$\mathrm{NLO}_{\mathrm{QCD}}$		$14.86(1)^{+1.4\%}_{-6.0\%}$	0.951
NLO		$15.08(1)^{+1.5\%}_{-5.6\%}$	0.965

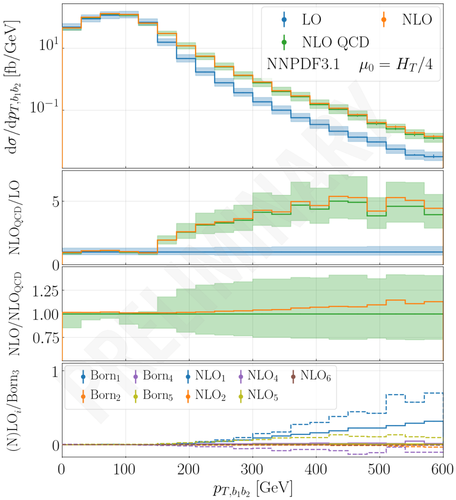


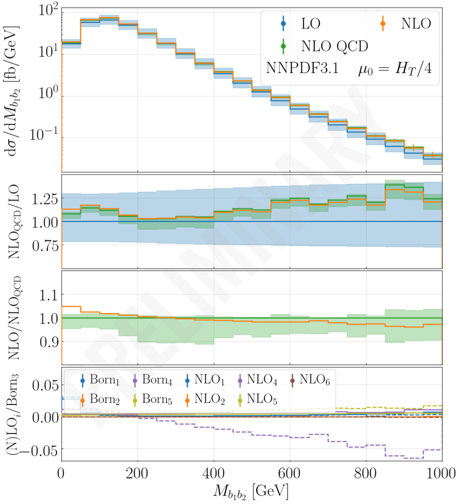
- **Cut:** $|m_{jj} - m_W| < 20$ GeV reduces QCD background
- Born_3 and NLO_3 dominate
- Subleading LO/NLO contribute $\lesssim 1\%$

$\mathrm{NLO}_{\mathrm{QCD}}$: $\mathrm{Born}_1 + \ldots + \mathrm{Born}_5 + \mathrm{NLO}_3$

Differential Distributions

(Mans, Stremmer, Worek, in preparation)





- p_{T,b_1b_2}: NLO_1 +50%, compared to leading $\mathrm{Born}_3 \Rightarrow \mathcal{O}(10\%)$ effect
- $M_{b_1b_2}$: EW Sudakov logarithm, $\mathcal{O}(-5\%)$

Summary and Outlook

- Full **NLO calculation** of $t\bar{t}$ in the **lepton + jets channel** posed significant challenges due to IR safety issues, which were successfully addressed through dedicated techniques.
- Preliminary results highlight the impact of complete NLO corrections at both the **Integrated fiducial level** and **Differential distribution level**
  - Born_3 and NLO_3 dominate, subleading LO/NLO contribute $\lesssim 1\%$
  - At the differential level, some enhanced subleading NLO effects compared to Born_3 in the tails of the distributions $\Rightarrow$ EW Sudakov logarithms in NLO_4
- This framework paves the way to compute **full off-shell, complete NLO corrections** in the semi-leptonic channel of other important $t\bar{t}$-associated production processes ($t\bar{t}H$, $t\bar{t}W^{\pm}$ etc.).

BACKUP

Setup and PDF choice

- **Collider:** pp at $\sqrt{s} = 13.6\,\text{TeV}$ (LHC Run III).
- **Scheme:** 5FS, massless b, diagonal CKM.
- **Coupling:** G_μ scheme with $G_\mu = 1.1663787 \times 10^{-5}\,\mathrm{GeV}^{-2}$.
- **PDF:** `NNPDF3.1luxQED_NLO` with $\alpha_s(m_Z) = 0.118$ (NNPDF 17).
- Photon content treated consistently with NLO QED corrections.

SM masses and widths (pole values)

Quantity	Mass [GeV]	Width [GeV]
M_W	80.377	2.085
M_Z	91.188	2.496
M_H	125.0	4.07×10^{-3}
m_t	172.5	1.352 (NLO QCD+EW)

Values follow PDG 2024 conversion to pole scheme (Bardin 88).

Dynamic scales, jet algorithm and cuts

Scale choices

- Central: $\mu_R = \mu_F = \mu_0$.
- *Option 1*: $\mu_0 = E_T/4$, with $E_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2}$.
- *Option 2*: $\mu_0 = H_T/4$, scalar sum of transverse momenta of visible final states.
- Uncertainty: 7-point variation $\{(2,1),(0.5,1),(1,2),(1,1),(1,0.5),(2,2),(0.5,0.5)\}$.

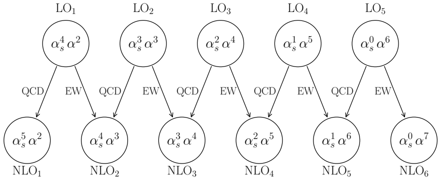
Jet algorithm cuts

- anti-k_T algorithm ($R = 0.4$) with FastJet.
- Democratic clustering with $z_{\gamma,\text{cut}} = 0.7$.
- Acceptance: $p_T > 25\,\text{GeV}$, $|y| < 2.5$ for μ^-, b-jets, light jets.
- Separation: $\Delta R_{bb,jb,\ell b,\ell j,jj} > 0.4$.
- Event topology: $\mu^- \bar{\nu}_\mu b\bar{b}jj$ with ≥ 2 b-jets, ≥ 2 light jets.
- Optional W-mass window Q_cut: $|M_{jj} - M_W| < 20\,\text{GeV}$.

Integrated Fiducial Cross-sections

(Mans, Stremmer, Worek, in preparation)

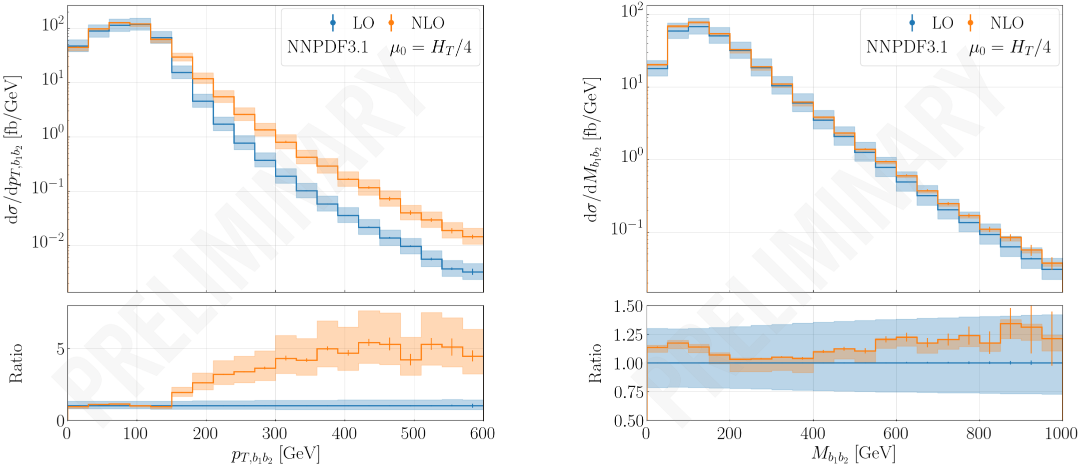
		σ_i [pb]	Ratio to Born_3
Born_1	$\mathcal{O}(\alpha_s^4\alpha^2)$	0.389(2)	2.40%
Born_2	$\mathcal{O}(\alpha_s^3\alpha^3)$	0.00106(5)	0.01%
Born_3	$\mathcal{O}(\alpha_s^2\alpha^4)$	16.194(2)	100.00%
Born_4	$\mathcal{O}(\alpha_s^1\alpha^5)$	0.06825(8)	0.42%
Born_5	$\mathcal{O}(\alpha_s^0\alpha^6)$	0.04990(3)	0.31%
NLO_1	$\mathcal{O}(\alpha_s^5\alpha^2)$	+ 0.110(3)	+ 0.68%
NLO_2	$\mathcal{O}(\alpha_s^4\alpha^3)$	− 0.0086(4)	− 0.05%
NLO_3	$\mathcal{O}(\alpha_s^3\alpha^4)$	+ 8.28(1)	+ 51.15%
NLO_4	$\mathcal{O}(\alpha_s^2\alpha^5)$	+ 0.096(1)	+ 0.59%
NLO_5	$\mathcal{O}(\alpha_s^1\alpha^6)$	+ 0.1382(5)	+ 0.85%
NLO_6	$\mathcal{O}(\alpha_s^0\alpha^7)$	+ 0.001176(8)	+ 0.01%
LO		$14.448(1)^{+31.2\%}_{-22.2\%}$	0.892
Born		$16.702(2)^{+31.2\%}_{-22.2\%}$	1.031
$\mathrm{NLO}_{\mathrm{QCD}}$		$24.99(1)^{+15.1\%}_{-13.5\%}$	1.543
NLO		$25.32(1)^{+14.2\%}_{-13.2\%}$	1.564



- No cut on m_{jj}
- Born_3 and NLO_3 dominate
- Subleading LO/NLO contribute $\lesssim 1\%$ except Born_1

Differential Distributions K-factor

(Mans, Stremmer, Worek, in preparation)



Differential Distributions without Q_{cut}

(Mans, Stremmer, Worek, in preparation)