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Top-quark pair production with two isolated photons at NLO QCD

Daniel Stremmer

In collaboration with: Malgorzata Worek

Based on JHEP 08 (2023) 179

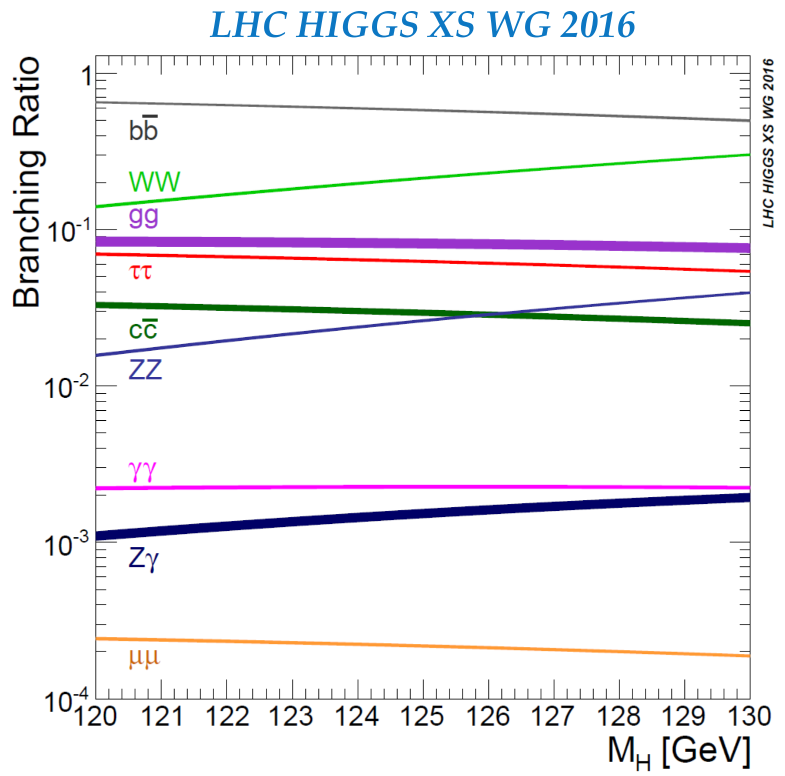
TTK Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

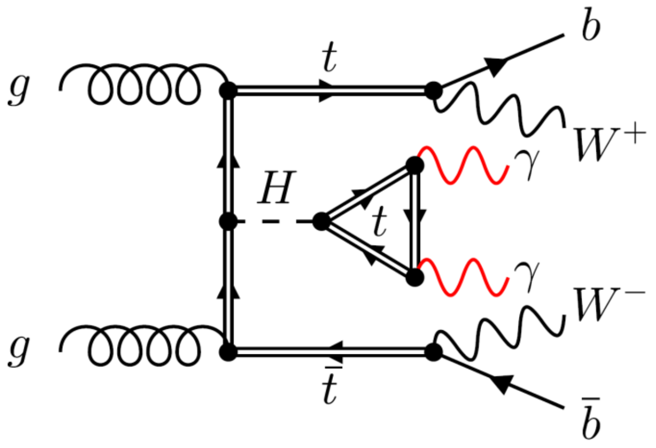
Collaborative Research Center TRR 257
P³H
Particle Physics Phenomenology after the Higgs Discovery

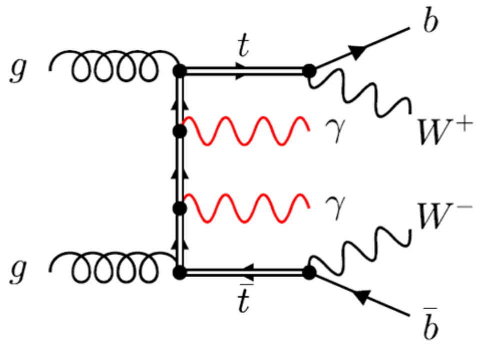
Young Scientists Meeting of the CRC TRR 257, Siegen, 17 October 2023

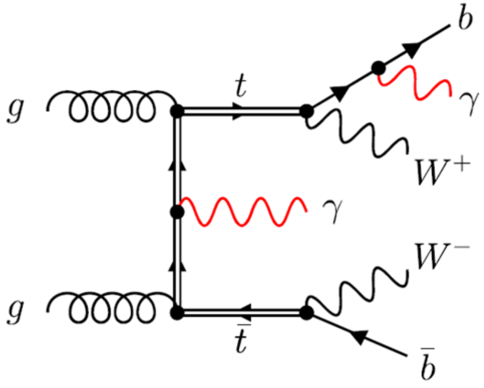
Motivation

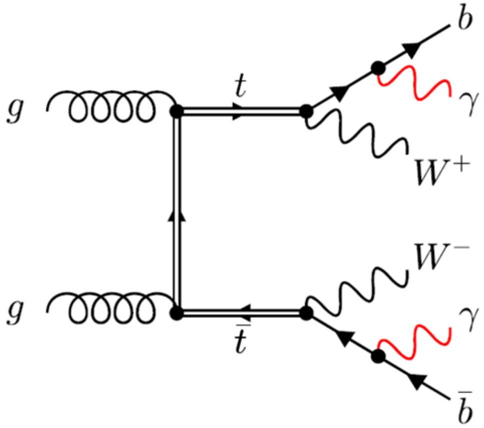
- Observation of $pp \to t\bar{t}H$ in 2018 by ATLAS and CMS
  Phys.Lett.B 784 (2018) 173-191
  Phys.Rev.Lett. 120 (2018) 23, 231801
- Direct probe of Y_t at tree level
- $H \to \gamma\gamma$ small branching ratio with $\sim 0.2\%$
- $pp \to t\bar{t}H(H \to \gamma\gamma)$ first single-channel observation of $pp \to t\bar{t}H$
  Phys.Rev.Lett. 125 (2020) 6, 061801
  Phys.Rev.Lett. 125 (2020) 6, 061802
- Large irreducible background from direct photon production $pp \to t\bar{t}\gamma\gamma$







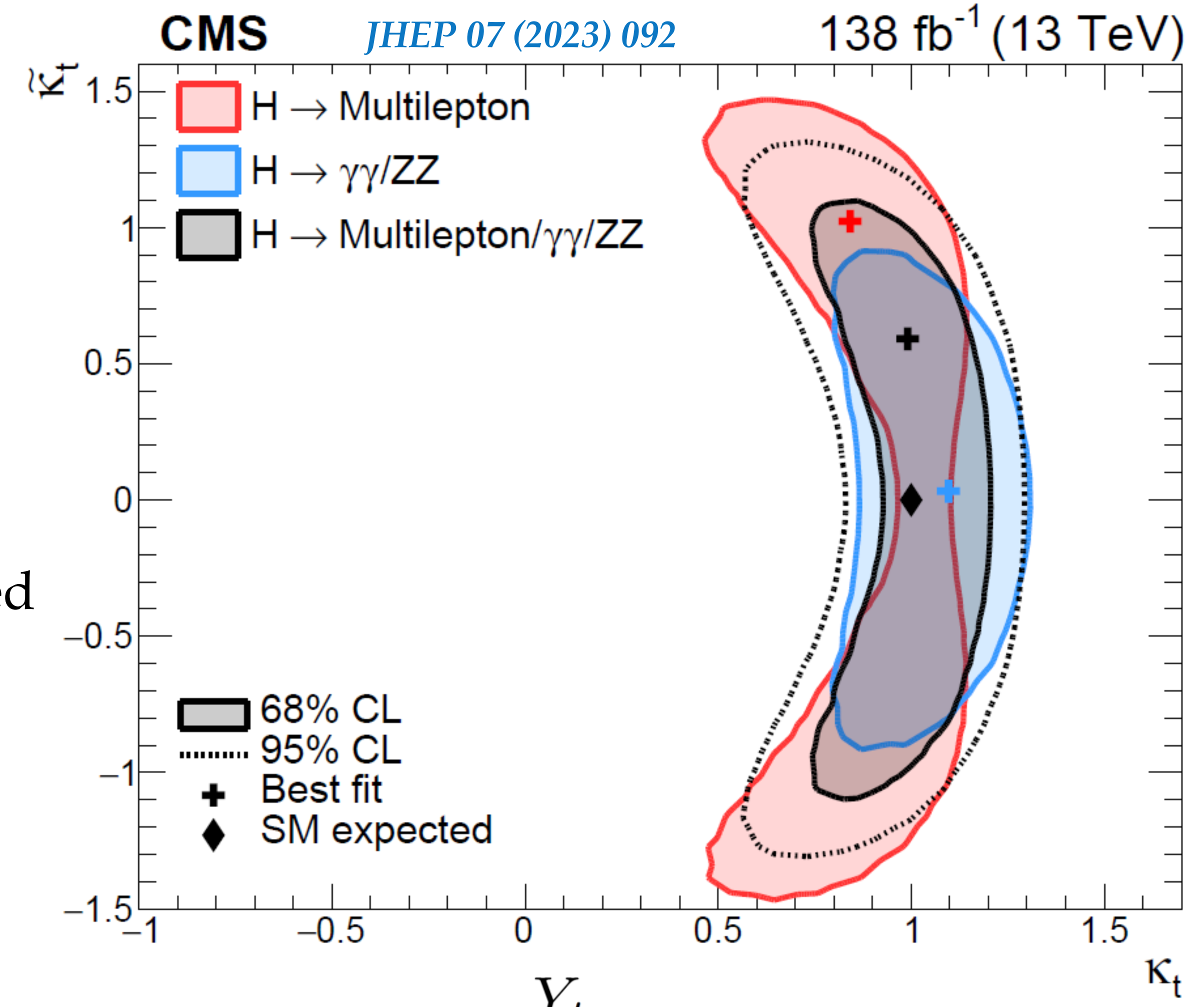




Feynman diagrams created with FeynGame   Harlander, Klein, Lipp '20

Motivation

- In SM: Higgs is CP-even ($\kappa_t = 1,\ \tilde{\kappa}_t = 0$)
- Pure CP-odd Higgs excluded with 3.9σ (ATLAS, *Phys.Rev.Lett. 125 (2020) 6, 061802*) and 3.7σ (CMS, *JHEP 07 (2023) 092*)
- Possible admixture between CP-even and CP-odd coupling
- Deviations from SM prediction can be interpreted in context of BSM:
  - Extended Higgs sector
  - 2HDM
  - …



$$\mathcal{L}_{t\bar{t}H} = -\bar{\psi}_t \frac{Y_t}{\sqrt{2}} \left(\kappa_t + i\tilde{\kappa}_t \gamma_5\right) \psi_t\, H$$

Theory status ($t\bar{t}\gamma\gamma$)

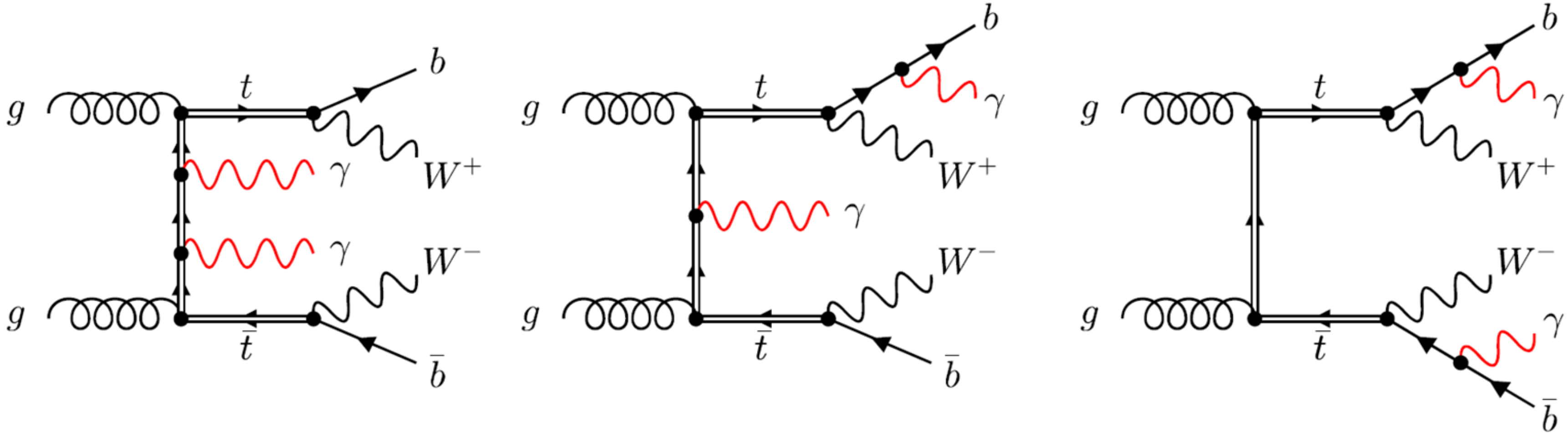
State of the art: **NLO QCD+EW**

- Stable top quarks at NLO QCD
  - $pp \to t\bar{t}\gamma\gamma$ — *Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro '14*; *Maltoni, Pagani, Tsinikos '16*
  - $pp \to t\bar{t}\gamma\gamma$ (NLO QCD+EW) — *Pagani, Shao, Tsinikos, Zaro '21*
- Matched to Parton Showers at NLO QCD
  - POWHEL/POWHEG — *Kardos, Trócsányi '15*
  - MC@NLO — *van Deurzen, Frederix, Hirschi, Luisoni, Mastrolia '16*

Setup

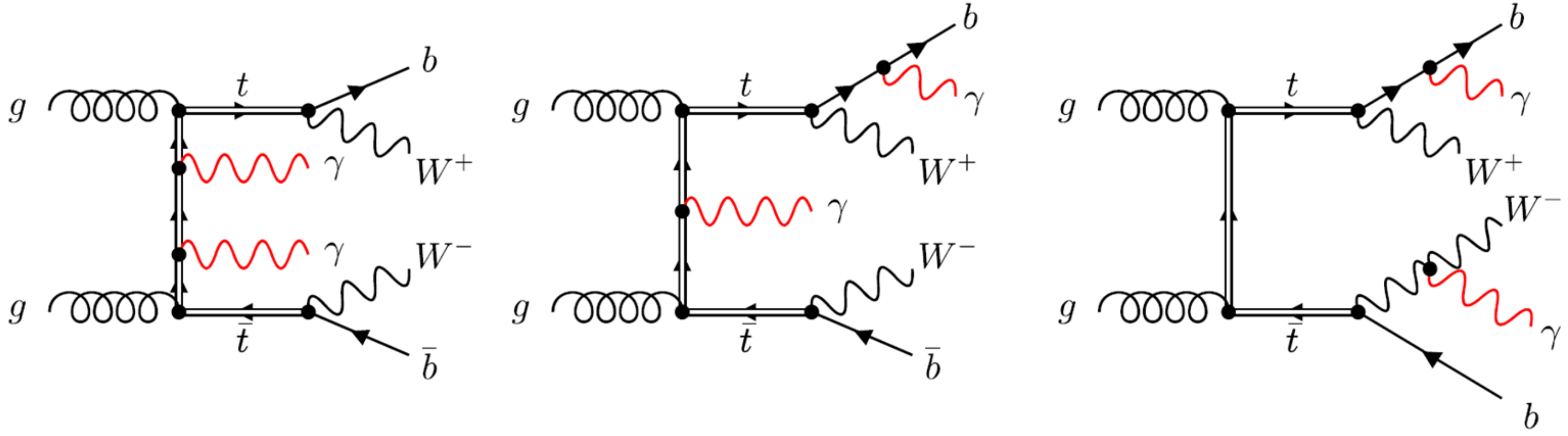
$$pp \to t\bar{t}(\gamma\gamma) \to W^+W^-b\bar{b}(\gamma\gamma) \to \begin{cases} \ell^+\ell^-\,\nu_\ell\bar{\nu}_\ell\, b\bar{b}\,\gamma\gamma \\ \ell^-\bar{\nu}_\ell\, jj\, b\bar{b}\,\gamma\gamma \end{cases} \qquad \ell^\pm = e^\pm, \mu^\pm$$

- LHC with $\sqrt{s} = 13$ TeV
- Calculation performed in Narrow Width Approximation preserving spin correlations
- Photon bremsstrahlung and NLO QCD corrections included in $t\bar{t}$ production and decay
- Diagonal CKM matrix
- 5 flavour scheme ($m_b = 0$)
- Top-quark width treated as fixed parameter ($\Gamma_t^{NLO}(\mu_R = m_t)$)



Process definition

$$d\sigma^{\rm LO}_{t\bar{t}\gamma\gamma} = \Gamma_t^{-2}\Big(\underbrace{d\sigma^{\rm LO}_{t\bar{t}\gamma\gamma}\, d\Gamma^{\rm LO}_{t\bar{t}}}_{\rm Prod.} + \underbrace{d\sigma^{\rm LO}_{t\bar{t}\gamma}\, d\Gamma^{\rm LO}_{t\bar{t}\gamma}}_{\rm Mixed} + \underbrace{d\sigma^{\rm LO}_{t\bar{t}}\, d\Gamma^{\rm LO}_{t\bar{t}\gamma\gamma}}_{\rm Decay}\Big)$$



- Full calculation divided into three resonant contributions: Prod., Mixed and Decay
- NLO QCD corrections calculated for each resonant structure separately

Computational framework

Virtual Corrections

- Recola *(Actis, Denner, Hofer, Lang, Scharf, Uccirati '17)* + Collier *(Denner, Hofer, Dittmaier, Hofer '17)*

- Cross-checked with HELAC-1LOOP *(van Hameren, Papadopoulos, Pittau '09)* with CutTools *(Ossola, Papadopoulos, Pittau '09)* and OneLOop *(van Hameren '11)*

Real Corrections in Helac-Dipoles

- Nagy-Soper subtraction *Bevilacqua, Czakon, Kubocz, Worek '13*
  - Extended to radiative decays

- Cross-checked with Catani-Seymour subtraction *Catani, Seymour '97* *Catani, Dittmaier, Seymour, Trocsanyi '02*

- Theoretical prediction are stored in modified Les Houches Event Files (LHEFs) *Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre '14*

- Reweighting to different renormalisation/factorisation scales and PDF sets

Setup of the calculation

- G_μ scheme: $\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right)$
- External photon radiation with $\alpha^{-1} = \alpha^{-1}(0) = 137.035999084$
- Renormalisation/Factorisation scale: $\mu_R = \mu_F = \mu_0 = \frac{E_T}{4}$ $\quad E_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} + p_{T,\gamma_1} + p_{T,\gamma_2}$
- NNPDF3.1 NLO PDF set with $\alpha_s(M_Z) = 0.118$ *Ball et. al. '17*

- Smooth photon isolation prescription *Frixione '98*

$$\sum_i E_{T\,i}\, \Theta(R - R_{\gamma i}) \leq \epsilon_\gamma\, E_{T\,\gamma} \left(\frac{1 - \cos(R)}{1 - \cos(R_{\gamma j})}\right)^n \qquad \text{for all } R \leq R_{\gamma j}$$

- with $R_{\gamma j} = 0.4$ and $\epsilon_\gamma = n = 1$
- Anti-k_T jet algorithm ($R = 0.4$) *Cacciari, Salam, Soyez '08*

Integrated Fiducial cross section in di-lepton channel

$$pp \to t\bar{t}(\gamma\gamma) \to W^+W^-b\bar{b}(\gamma\gamma) \to \ell^+\ell^- \nu_\ell\bar{\nu}_\ell b\bar{b}\gamma\gamma$$

μ_0			LO	NLO	$\mathcal{K} = \sigma_{\rm NLO}/\sigma_{\rm LO}$
$E_T/4$	$\sigma_{\rm Full}$	[fb]	$0.13868(3)^{+31.2\%}_{-22.1\%}$	$0.1773(1)^{+1.8\%}_{-6.2\%}$	1.28
	$\sigma_{\rm Prod.}$	[fb]	$0.05399(2)^{+30.6\%}_{-21.7\%}$	$0.07130(6)^{+2.5\%}_{-7.2\%}$	1.32
	$\sigma_{\rm Mixed}$	[fb]	$0.06022(2)^{+31.9\%}_{-22.5\%}$	$0.07733(8)^{+1.5\%}_{-6.2\%}$	1.28
	$\sigma_{\rm Decay}$	[fb]	$0.024473(7)^{+30.9\%}_{-22.1\%}$	$0.02863(4)^{+0.9\%}_{-4.9\%}$	1.17

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- NLO QCD corrections ~30%
- Scale uncertainties reduced from 31% to 6%
- Relative size to Full: Prod. (40%), Mixed (44%) and Decay (16%)
- Internal PDF uncertainties: NNPDF3.1 1.0%, MSHT20 1.4%, CT18 2.0%

Resonant contributions

		gg	gg/pp	$q\bar{q}$	$q\bar{q}/pp$	$qg+\bar{q}g$	$(qg+\bar{q}g)/pp$
$\sigma^{\text{NLO}}_{\text{Full}}$	[fb]	0.0999(1)	56.4%	0.04307(4)	24.3%	0.03428(4)	19.3%
$\sigma^{\text{NLO}}_{\text{Prod.}}$	[fb]	0.02587(4)	36.3%	0.02672(4)	37.5%	0.01871(3)	26.2%
$\sigma^{\text{NLO}}_{\text{Mixed}}$	[fb]	0.04928(8)	63.7%	0.01408(2)	18.2%	0.01398(2)	18.1%
$\sigma^{\text{NLO}}_{\text{Decay}}$	[fb]	0.02476(4)	86.5%	0.002268(3)	7.9%	0.00160(2)	5.6%

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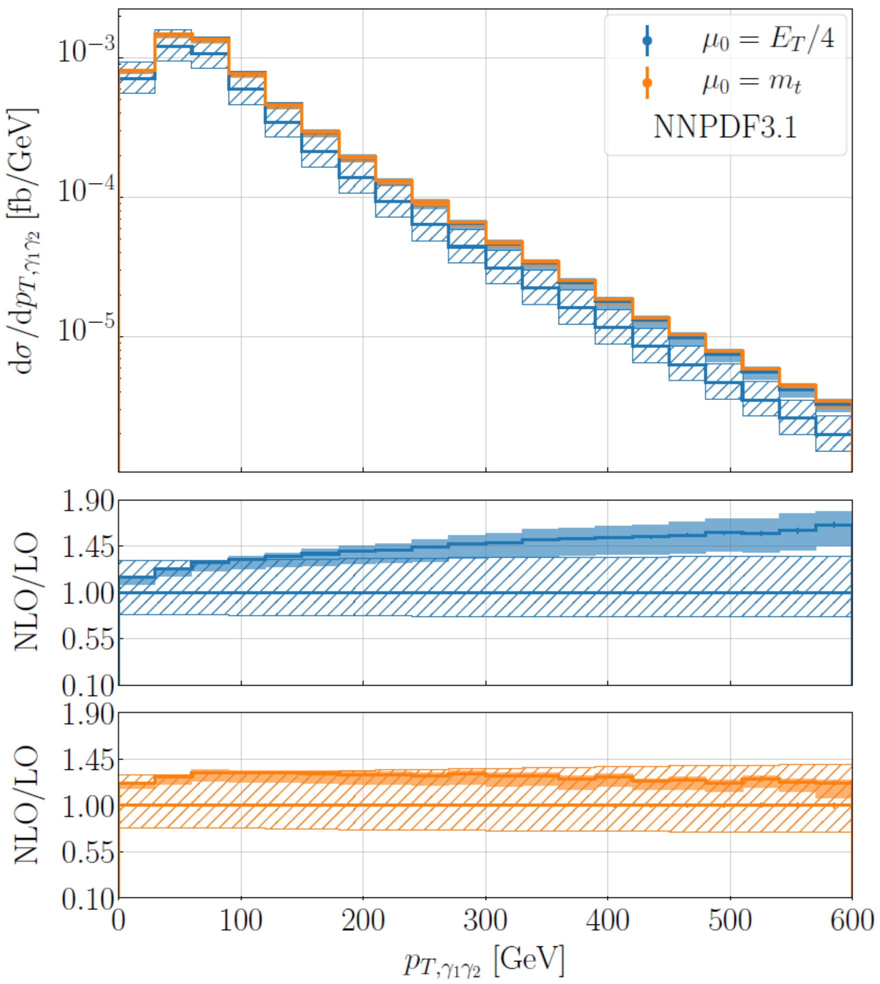
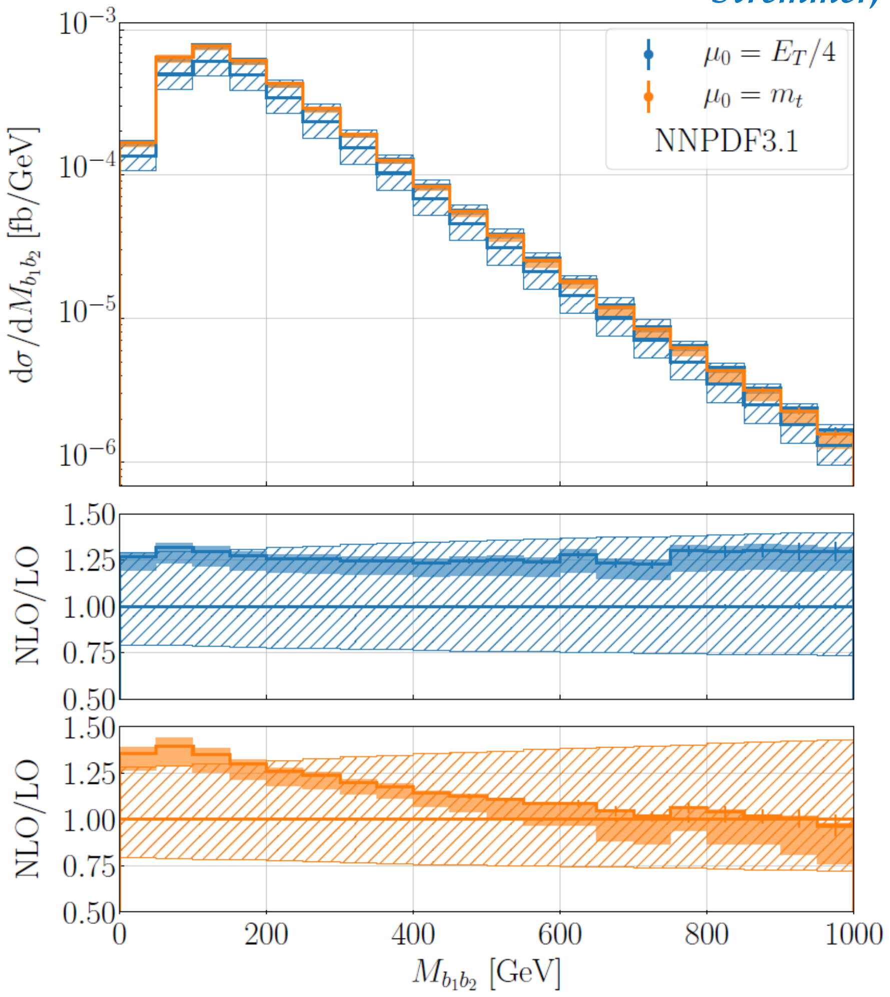
- Full dominated by gg with 56.4%
- $q\bar{q}$ channel decreases, gg channel increases in absolute size from Prod. to Mixed
- gg channel supressed for increasing number of photons in $t\bar{t}$ production
- Conclusions also hold in lepton + jet top-quark decay channel

Differential Fiducial cross section

Stremmer, Worek '23



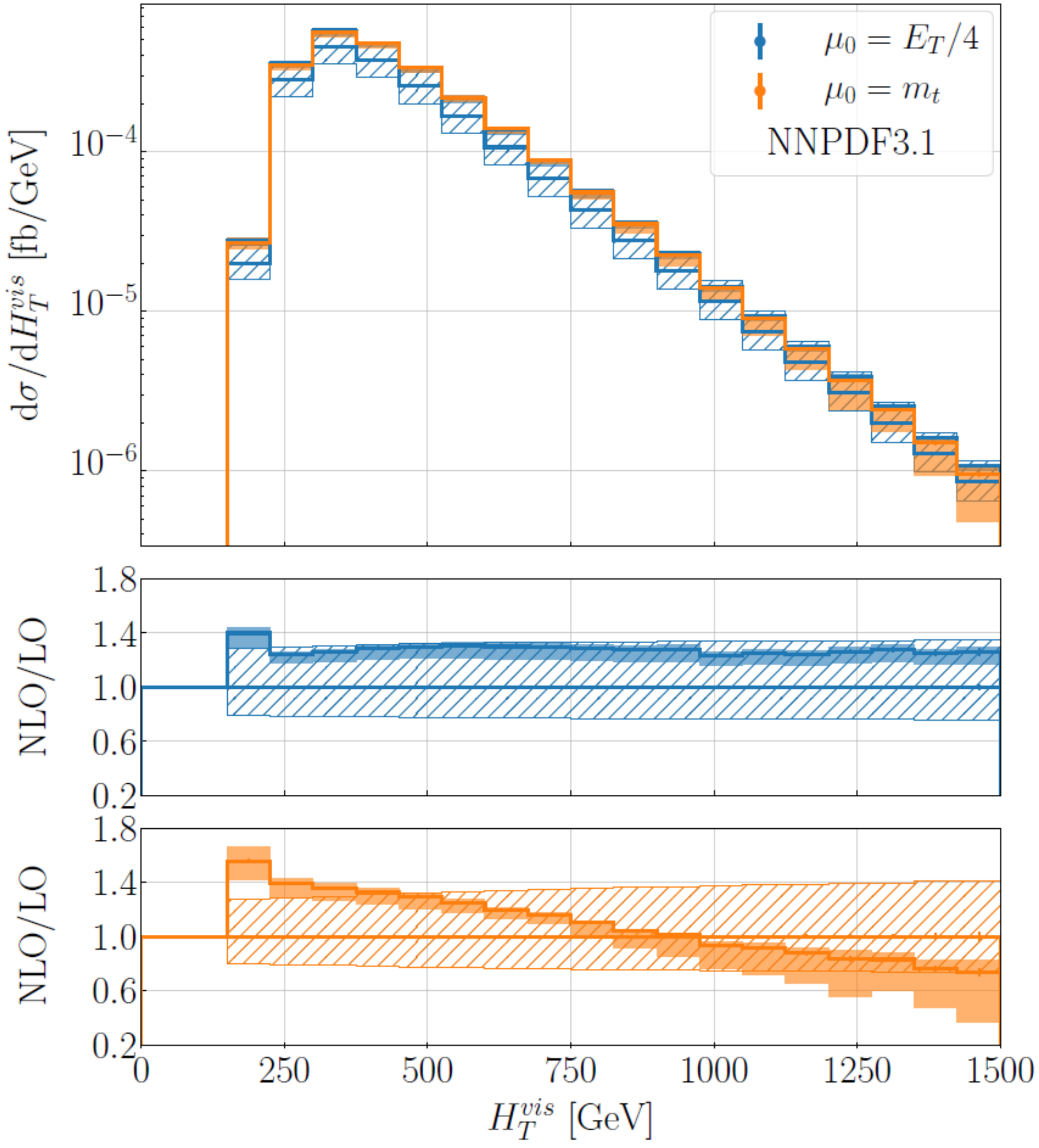


- NLO QCD corrections up to 65%
- Smaller corrections for $\mu_0 = m_t$
- Scale uncertainties $5\% - 13\%$

- NLO QCD corrections $\sim 25\% - 30\%$
- Scale uncertainties reduced from $\sim 35\%$ to $5\% - 8\%$
- Increasing scale uncertainties in tails for $\mu_0 = m_t$

Differential Fiducial cross section

Stremmer, Worek '23



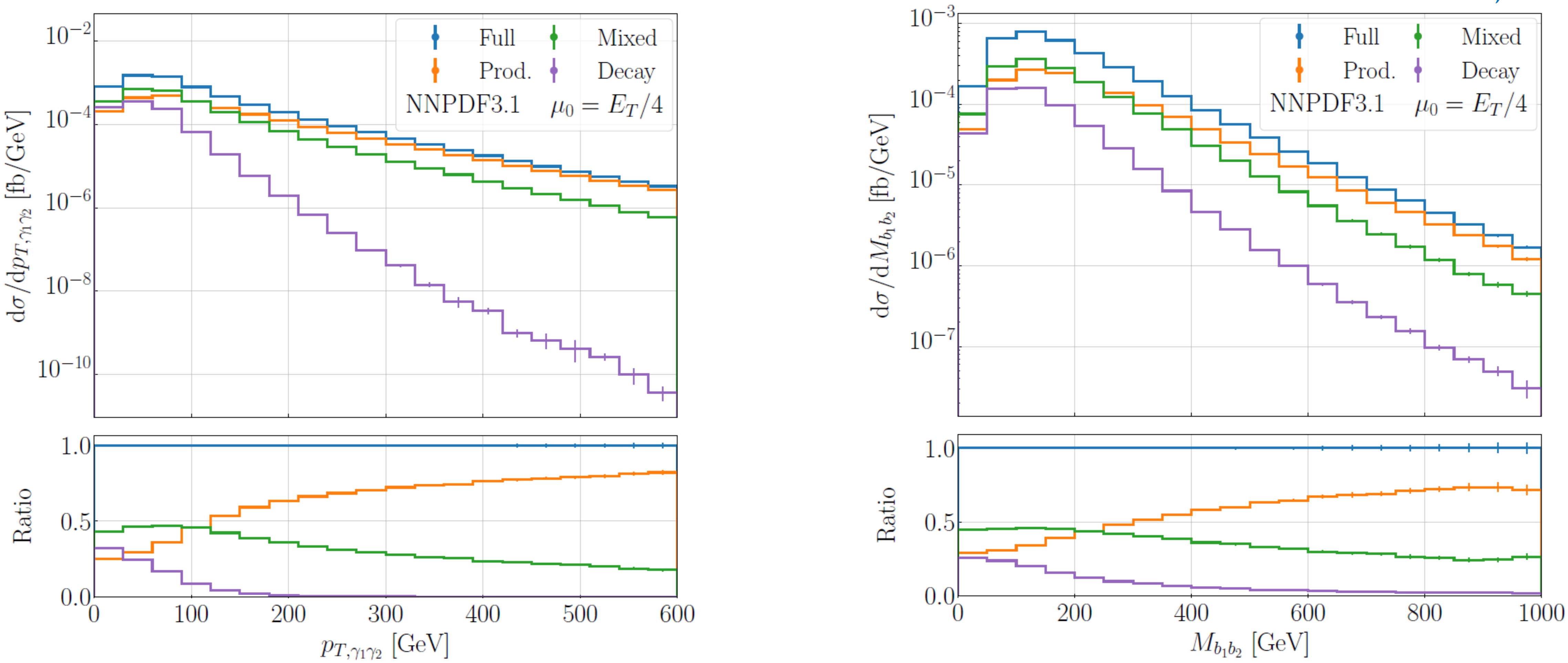
$$H_T^{vis} = p_{T,\ell^+} + p_{T,\ell^-} + p_{T,b_1} + p_{T,b_2} + p_{T,\gamma_1} + p_{T,\gamma_2}$$

- Fixed scale unstable for general dimensionful observables:
  - Large shape distortions
  - NLO scale uncertainties, up to 50%, exceeding LO ones

→ Dynamical scale in general required

Resonant contribution

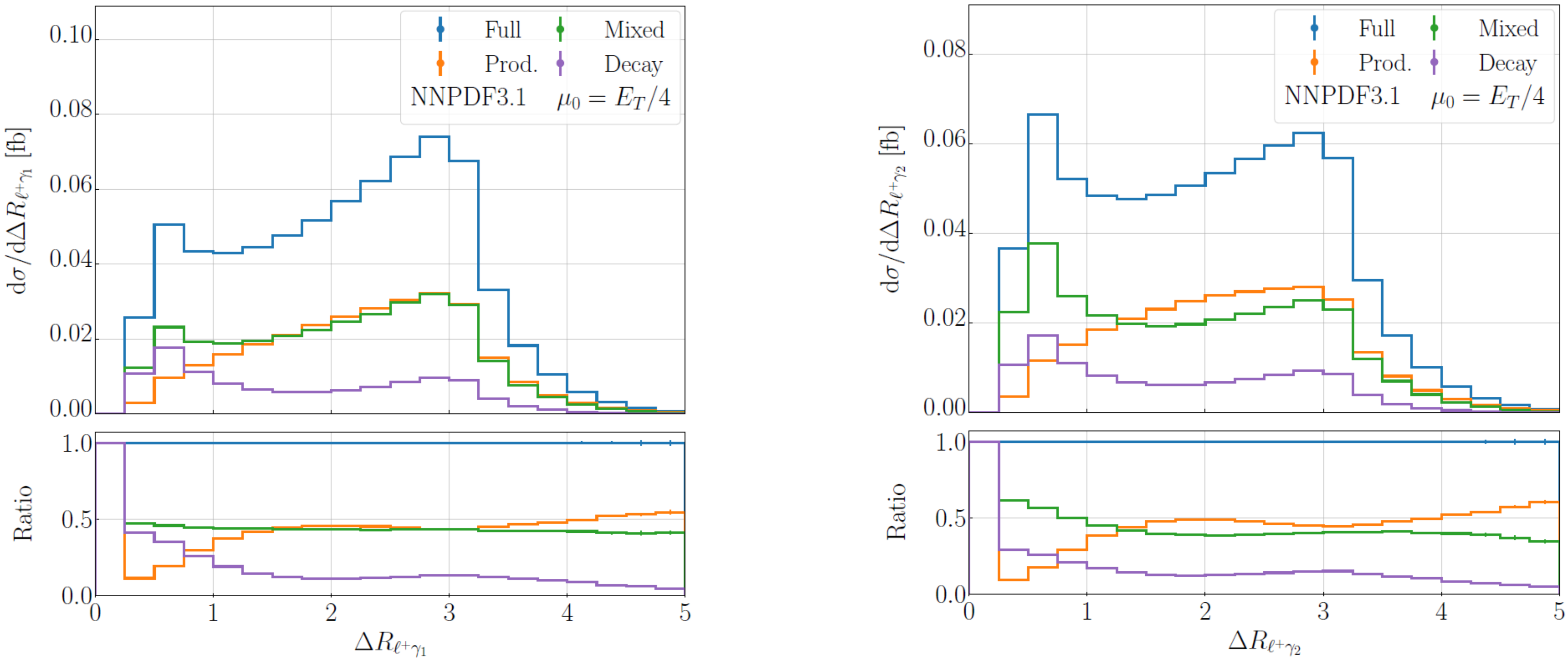
Stremmer, Worek '23



- Large contributions from photon emission in decays in bulk of distribution
- Tails dominated by Prod. (79 – 82% of Full)
- Decay less suppressed in tails of non-photonic observables

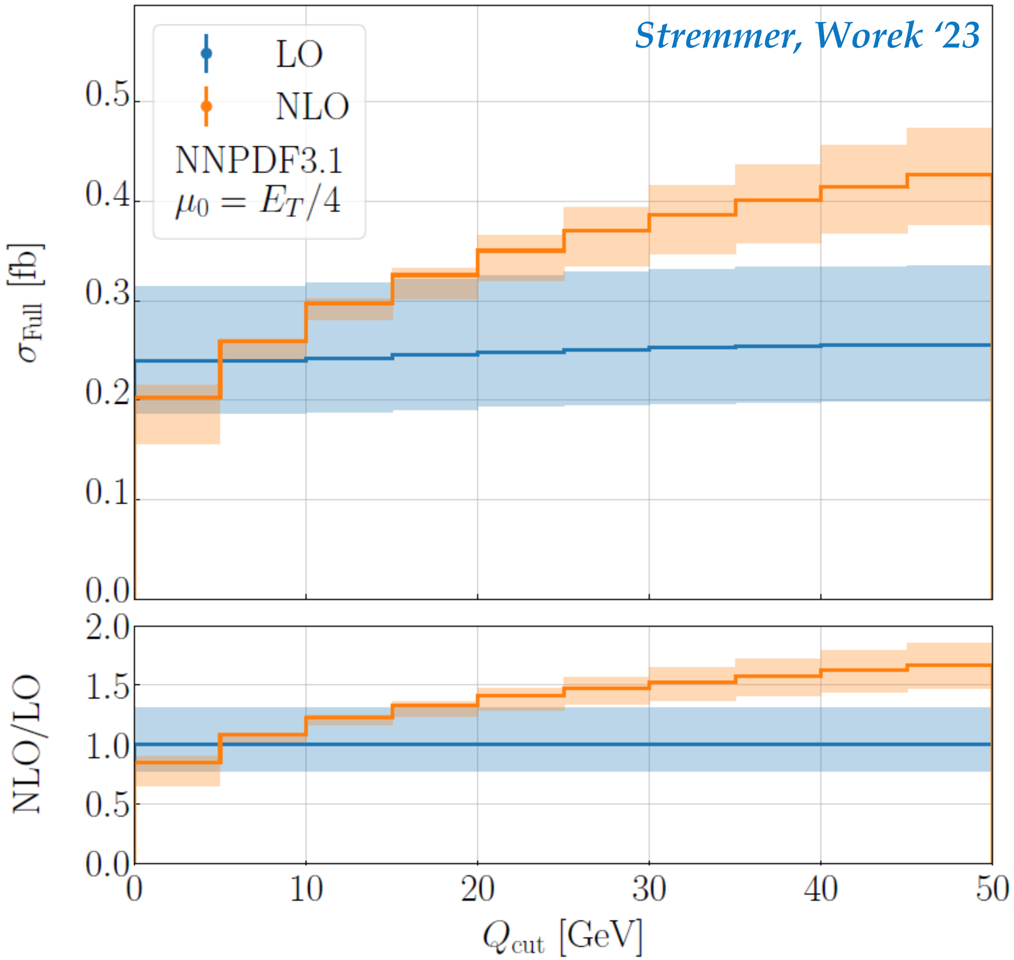
Resonant contribution

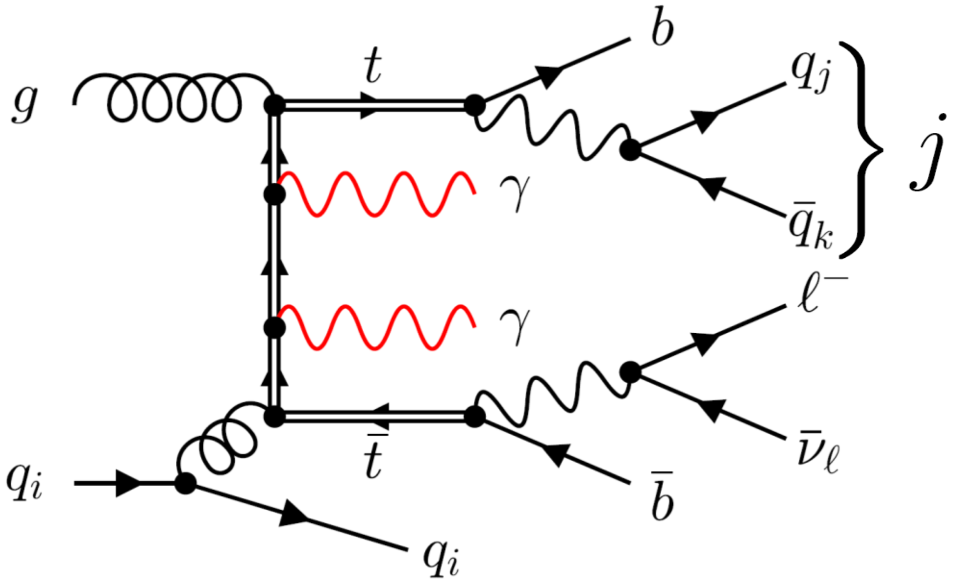
Stremmer, Worek '23



- Different peak structures for Prod., Mixed and Decay
- Only sum leads to reliable predictions

Integrated Fiducial cross section in lepton + jet channel





- Large NLO QCD corrections of ~140% for $Q_{\text{cut}} \to \infty$ caused by hard radiation in production stage
- NLO QCD corrections drastically reduced by additional $|m_W - M_{jj}| < Q_{\text{cut}}$

Integrated Fiducial cross section in lepton + jet channel

$$|m_W - M_{jj}| < 15 \text{ GeV}$$

μ_0			LO	NLO	$\mathcal{K} = \sigma_{\text{NLO}}/\sigma_{\text{LO}}$
$E_T/4$	σ_{Full}	[fb]	$0.24214(4)^{+31.1\%}_{-22.0\%}$	$0.2973(3)^{+1.9\%}_{-5.4\%}$	1.23
	$\sigma_{\text{Prod.}}$	[fb]	$0.11960(3)^{+30.5\%}_{-21.6\%}$	$0.1405(2)^{+2.1\%}_{-4.6\%}$	1.17
	σ_{Mixed}	[fb]	$0.09632(3)^{+31.9\%}_{-22.5\%}$	$0.1205(2)^{+1.5\%}_{-5.7\%}$	1.25
	σ_{Decay}	[fb]	$0.026230(9)^{+30.9\%}_{-22.1\%}$	$0.03629(7)^{+3.3\%}_{-7.7\%}$	1.38

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- NLO corrections ~23%, scale uncertainties reduced from ~31% to ~5%

- Prod. increased from 40% (di-lepton) to 48% (lepton + jet) because of by additional cut

$$\sigma^{\text{NLO}}_{\text{Full}}(\epsilon_\gamma = 0.5) = 0.2832(7) \text{ fb}$$
$$\sigma^{\text{NLO}}_{\text{Full}}(E_{T\,\gamma}\,\epsilon_\gamma = 10 \text{ GeV}) = 0.2666(8) \text{ fb}$$

$$\sum_i E_{T\,i}\,\Theta(R - R_{\gamma i}) \leq \epsilon_\gamma\, E_{T\,\gamma} \left(\frac{1-\cos(R)}{1-\cos(R_{\gamma j})}\right)^n$$

- Significant deviations (5% – 10%) between different input parameters in Smooth photon isolation prescription

Differential Fiducial cross section in lepton + jet channel

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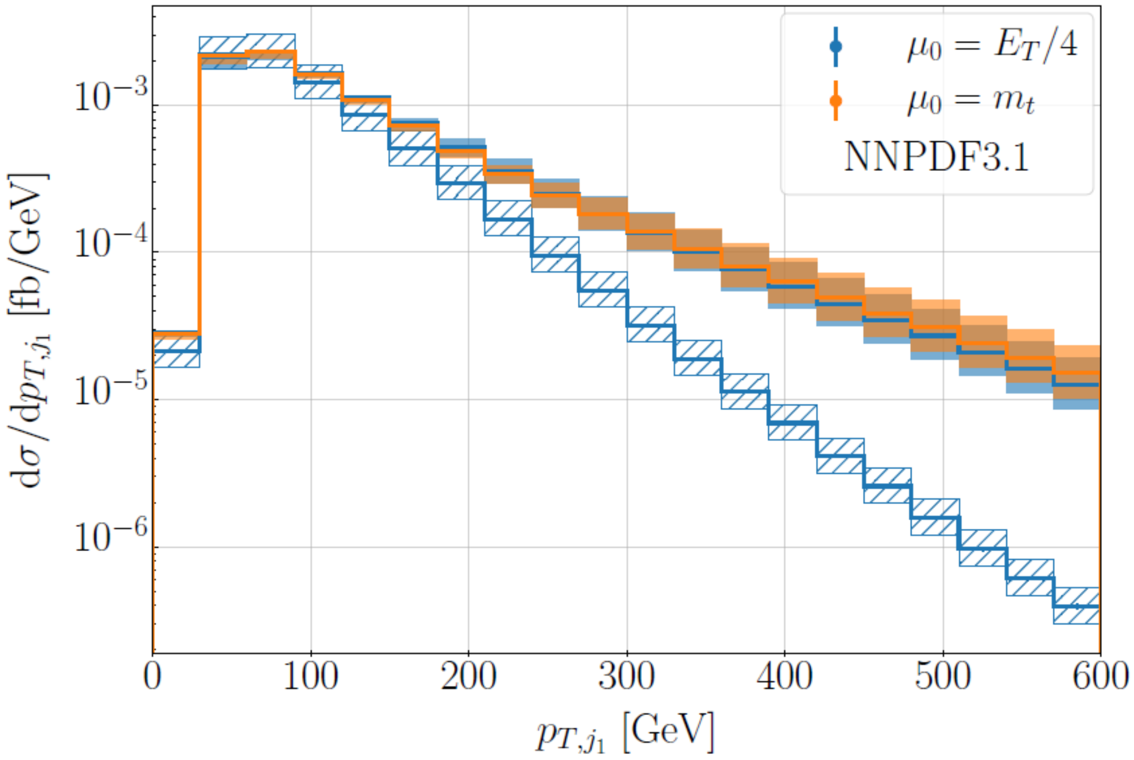

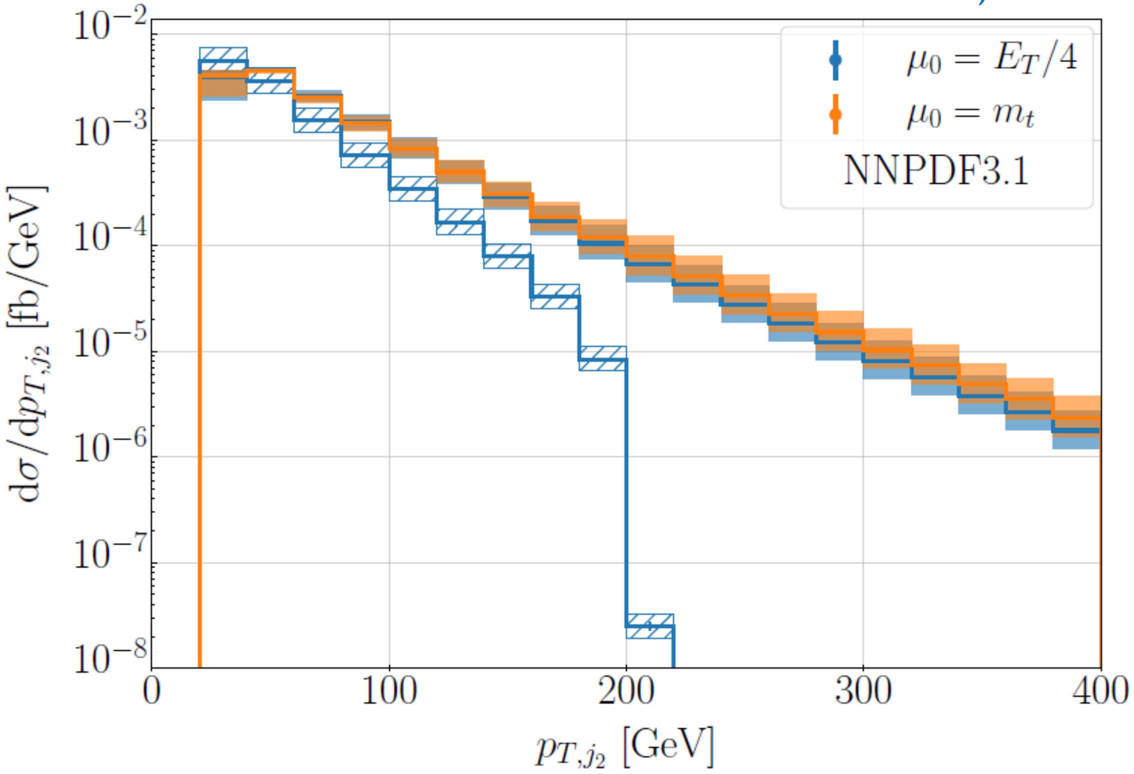

- Huge NLO QCD corrections caused by hard jets in the production stage
- Scale uncertainties in tails ~50%

- LO spectrum limited by finite W boson mass $p_{T,j_2,max} \sim m_W/\Delta R_{jj} \sim 203$ GeV
- Scale uncertainties in tails ~50%

Conclusion

- NLO QCD corrections to $pp \to t\bar{t}(\gamma\gamma) \to W^+W^-b\bar{b}(\gamma\gamma) \to \begin{cases} \ell^+\ell^-\,\nu_\ell\bar{\nu}_\ell\,b\bar{b}\,\gamma\gamma \\ \ell^-\bar{\nu}_\ell\,jj\,b\bar{b}\,\gamma\gamma \end{cases}$
- Photon bremsstrahlung consistenly included in production and decay of top-quark pair
- Only 40% – 48% of integrated fiducial cross section from Prod.
- Large NLO QCD corrections in lepton + jet channel reduced by additional cut ($|m_W - M_{jj}| < 15$ GeV)
- Still huge NLO QCD corrections in hadronic observables
- Large dependence on input parameters in Smooth photon isolation prescription

Outlook

- Realistic photon isolation based on Fixed Cone Isolation or Democratic Clustering
  → Requires QED subtraction, quark-to-photon and gluon-to-photon fragmentation functions

Backup

Setup of the calculation (2)

- Exclusive in $n_b = 2$

- Event selection:

$$p_{T,\ell} > 25 \text{ GeV}\,, \qquad |y_\ell| < 2.5\,, \qquad \Delta R_{\ell\ell} > 0.4\,,$$

$$p_{T,b} > 25 \text{ GeV}\,, \qquad |y_b| < 2.5\,, \qquad \Delta R_{bb} > 0.4\,,$$

$$p_{T,\gamma} > 25 \text{ GeV}\,, \qquad |y_\gamma| < 2.5\,, \qquad \Delta R_{\gamma\gamma} > 0.4\,,$$

$$\Delta R_{bl} > 0.4\,, \qquad \Delta R_{\gamma l} > 0.4\,, \qquad \Delta R_{\gamma b} > 0.4$$

- Additional cuts in lepton+jet channel:

$$p_{T,j} > 25 \text{ GeV}\,, \qquad |y_j| < 2.5\,, \qquad \Delta R_{jj} > 0.4\,,$$

$$\Delta R_{\ell j} > 0.4\,, \qquad \Delta R_{bj} > 0.4\,, \qquad \Delta R_{\gamma j} > 0.4$$

$$|m_W - M_{jj}| < 15 \text{ GeV}$$