Research Training Group Physics of the Heaviest Particles at the LHC
RWTH AACHEN UNIVERSITY
TTK Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY
Collaborative Research Center TRR 257
P H
Particle Physics Phenomenology after the Higgs Discovery

Complete NLO corrections to top-quark pair production with isolated photons

Malgorzata Worek

Instead of Introduction

- Latest theoretical results for $pp \to tt\gamma$
  - Not only are they impressive, but there are plenty of them

- Tell story, hopefully interesting one
  - Based on many years of work & development of Helac-Nlo
  - *Processes with top-quark decays* $\to$ *Phenomenological results*
  - Various results for $pp \to tt\gamma$ & $pp \to tt\gamma\gamma$

- NLO QCD & Complete NLO

My Goal

- Identify which effects are important & should be included
- Give a few examples for **NLO QCD** results for $pp \to tt\gamma$ & $pp \to tt\gamma\gamma$
- Present **Complete NLO** results for $pp \to tt\gamma$ & $pp \to tt\gamma\gamma$ $\to$ Discuss approximated results
- Vital for
  - SM studies in top-quark sector
  - BSM searches in top-quark sector
  - SM Higgs boson measurements $\to$ $pp \to ttH$ $(H \to \gamma\gamma)$
- *(Biased) Selection* $\to$ Only (my) latest results $\to$ Only LHC

Outline

Focus of this talk:

- Top-quark pair production with isolated photons: $pp \to tt\gamma$ & $pp \to tt\gamma\gamma$
  - Top-quark decay channel → *di-lepton* decay channel
  - Modelling of unstable *t & W* bosons → $2 \to 7$ & $2 \to 8$ in NWA
- **NLO QCD** → QCD corrections & photon radiation included in production & decays
- **Complete NLO** → QCD & EW corrections & photon radiation included in production & decays
- NLO QCD results for $pp \to tt\gamma\gamma$
  - Results in NWA available also for *l+jets* decay channel

Bevilacqua, Hartanto, Kraus, Weber, Worek, JHEP 10 (2018) 158
Bevilacqua, Hartanto, Kraus, Weber, Worek, JHEP 03 (2020) 154
Stremmer, Worek, JHEP 08 (2023) 179
Stremmer, Worek e-Print: 2403.03796 [hep-ph]

Additional results with HELAC-NLO not discussed during this talk

- NLO QCD results for $pp \to tt\gamma$
  - Full off-shell predictions for *di-lepton* decay channel
  - Compared to ATLAS data

Bevilacqua, Hartanto, Kraus, Weber, Worek, JHEP 10 (2018) 158

Instead of Introduction → Experimental Results

$pp \to tt\gamma$

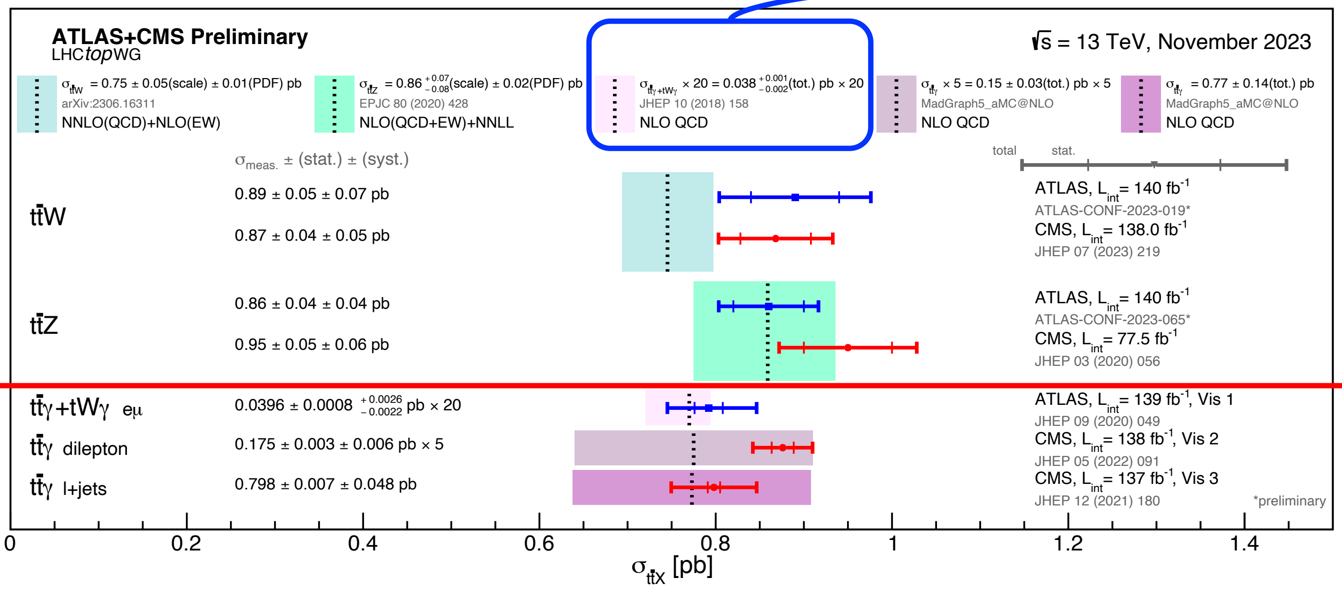
- $tt\gamma$ has been observed *@ LHC @ 7 TeV* by ATLAS
- Both ATLAS and CMS have observed $tt\gamma$ *@ LHC @ 8 TeV & 13 TeV*
- No significant deviations from SM predictions have been found
    - Measured cross sections are larger than theoretical predictions
    - Differential cross-section distributions described rather well by NLO theory predictions
    - Measurements in $pp \to tt\gamma$ process have also been interpreted in framework of SMEFT
    - Measurement of top-quark charge asymmetry in $pp \to tt\gamma$ has recently been performed by ATLAS

$pp \to tt\gamma\gamma$

- No observation for QCD $pp \to tt\gamma\gamma$ process @ LHC yet
- Observation of $pp \to ttH \to tt\gamma\gamma$

ATLAS, Phys. Rev. Lett. 125 (2020) 061802
CMS, Phys. Rev. Lett. 125 (2020) 061801

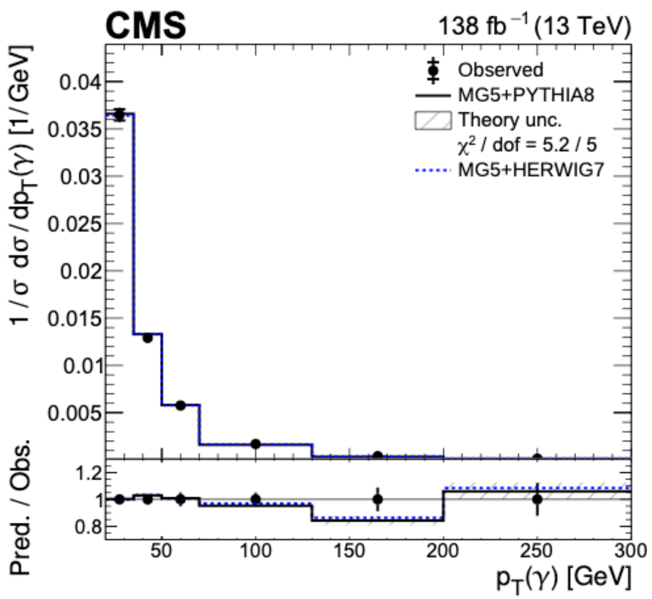
Instead of Introduction → Experimental Results

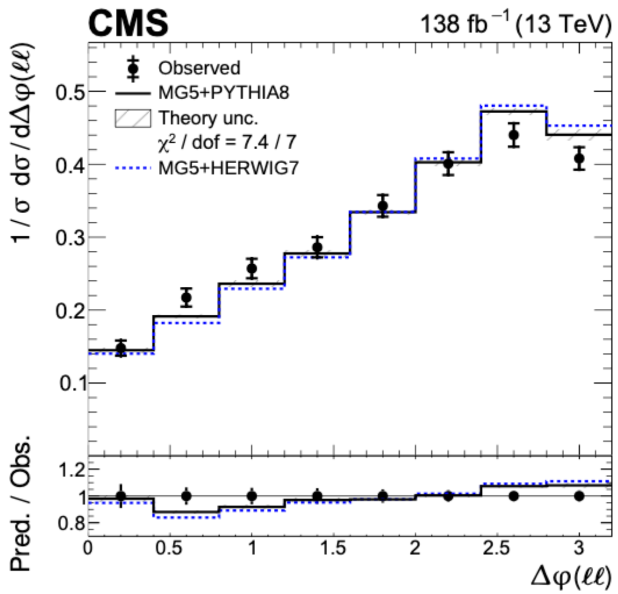


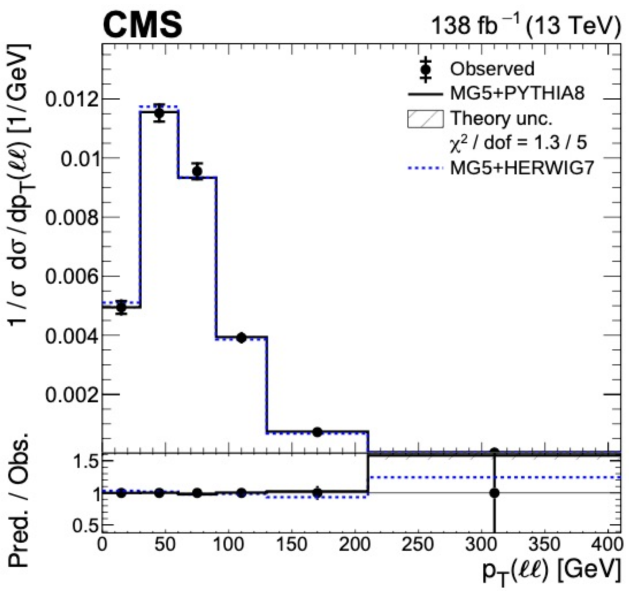
HELAC-NLO

$pp \to tt\gamma$ @ LHC_{13TeV}

CMS, JHEP 05 (2022) 091





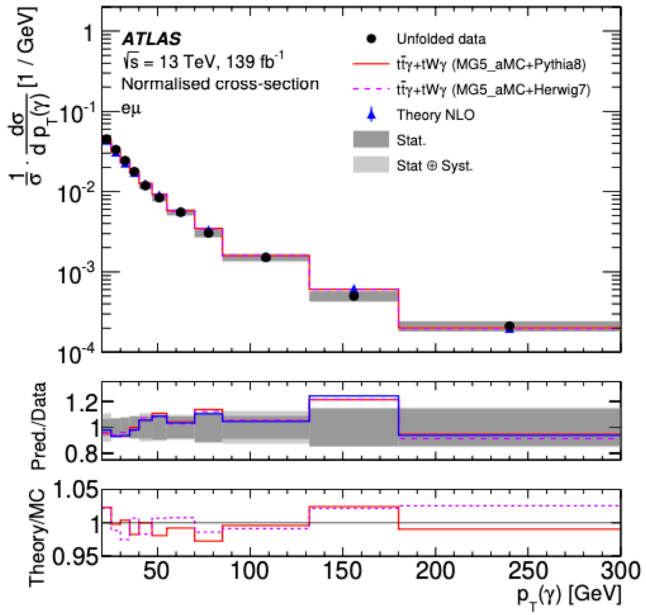


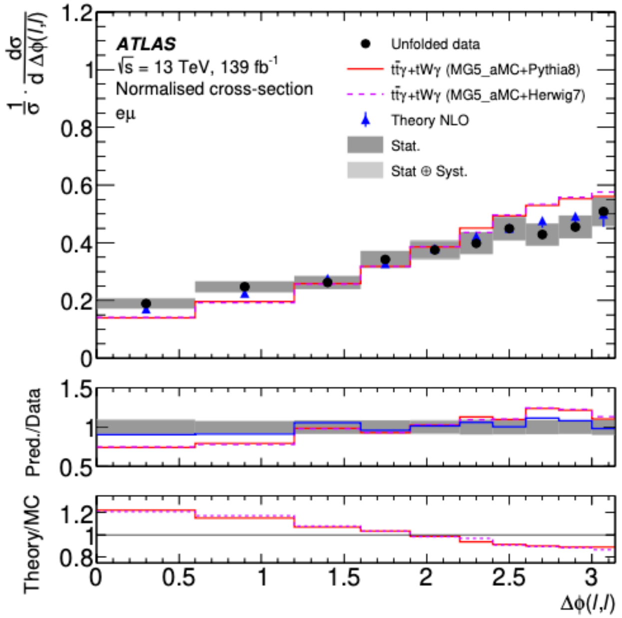
Instead of Introduction → Experimental Results

HELAC-NLO

Predictions	$p_T(\gamma)$ χ^2/ndf	$p_T(\gamma)$ p-value	$\lvert\eta(\gamma)\rvert$ χ^2/ndf	$\lvert\eta(\gamma)\rvert$ p-value	$\Delta R(\gamma,\ell)_{\min}$ χ^2/ndf	$\Delta R(\gamma,\ell)_{\min}$ p-value	$\Delta\phi(\ell,\ell)$ χ^2/ndf	$\Delta\phi(\ell,\ell)$ p-value	$\lvert\Delta\eta(\ell,\ell)\rvert$ χ^2/ndf	$\lvert\Delta\eta(\ell,\ell)\rvert$ p-value
$t\bar{t}\gamma$+$tW\gamma$ (MG5_aMC+Pythia8)	6.3/10	0.79	7.3/7	0.40	20.1/9	0.02	30.8/9	<0.01	6.5/7	0.48
$t\bar{t}\gamma$+$tW\gamma$ (MG5_aMC+Herwig7)	5.3/10	0.87	7.7/7	0.36	18.9/9	0.03	31.6/9	<0.01	6.8/7	0.45
Theory NLO	6.0/10	0.82	4.5/7	0.72	13.5/9	0.14	5.8/9	0.76	5.6/7	0.59

χ^2/ndf and p-values between measured normalised cross-sections and various predictions from MC simulations and NLO calculation





Category	Uncertainty
$t\bar{t}\gamma/tW\gamma$ modelling	3.8%
Background modelling	2.1%
Photons	1.9%
Luminosity	1.8%
Jets	1.6%
Pile-up	1.3%
Leptons	1.1%
Flavour-tagging	1.1%
MC statistics	0.4%
Soft term E_T^{miss}	0.2%
$tW\gamma$ parton definition	2.8%
Total syst.	6.3%

ATLAS, JHEP 09 (2020) 049

Theory NLO: *Bevilacqua, Hartanto, Kraus, Weber, Worek, JHEP 10 (2018) 158*

Theoretical Predictions

$pp \to t\bar{t}\gamma$

Predictions with Stable Top Quarks

- NLO QCD corrections

  Duan, Ma, Zhang, Han, Guo, Wang, Phys. Rev. D 80 (2009) 014022
  Duan, Zhang, Ma, Han, Guo, Wang, Chin. Phys. Lett. 28 (2011) 111401
  Maltoni, Pagani, Tsinikos, JHEP 02 (2016) 113

- NLO EW corrections $\rightarrow$ Significant effects in high energy region due to EW Sudakov effect

  Duan, Zhang, Wang, Song, Li, Phys. Lett. B 766 (2017) 102

- *Complete NLO predictions*

  Pagani, Shao, Tsinikos, Zaro, JHEP 09 (2021) 155

- Approximate NNLO with soft-gluon corrections added to NLO (QCD + EW)

  Kidonakis, Tonero, Phys. Rev. D 107 (2023) 034013

Theoretical Predictions

$pp \to tt\gamma$

Predictions with Top-Quark Decays

- NLO QCD predictions matched with parton shower programs
  - Top-quark decays treated in parton-shower approximation omitting spin correlations & photon emission in parton-shower evolution

Kardos, Trocsanyi, JHEP 05 (2015) 090

- NLO QCD with decays in NWA
  - Double-resonant top-quark contributions + unstable t & W restricted to on-shell states
  - NLO spin correlations & photon radiation off charged top-quark decay products

Melnikov, Schulze, Scharf, Phys. Rev. D 83 (2011) 074013
Bevilacqua, Hartanto, Kraus, Weber , Worek, JHEP 03 (2020) 154

- NLO QCD with full off-shell effects
  - Double-, single- & non-resonant contributions + interference effects + Breit-Wigner propagators
  - NLO spin correlations & photon radiation off charged top-quark decay products

Bevilacqua, Hartanto, Kraus, Weber, Worek, JHEP 10 (2018) 158

- *Complete NLO predictions in NWA*

Stremmer, Worek e-Print: 2403.03796 [hep-ph]

Theoretical Predictions

$pp \rightarrow tt\gamma\gamma$

Predictions with Stable Top Quarks

- NLO QCD corrections

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro, JHEP 07 (2014) 079
Maltoni, Pagani, Tsinikos, JHEP 02 (2016) 113

- NLO EW corrections

Pagani, Shao, Tsinikos, Zaro, JHEP 09 (2021) 155

Predictions with Top-Quark Decays

- NLO QCD predictions matched with parton shower programs omitting spin correlations & photon emission in parton-shower evolution or with LO spin correlations only

Kardos, Trocsanyi, Nucl. Phys. B 897 (2015) 717
Deurzen, Frederix, Hirschi, Luisoni, Mastrolia, Ossola, Eur. Phys. J. C 76 (2016) 221

- NLO QCD with decays in NWA

Stremmer, Worek, JHEP 08 (2023) 179

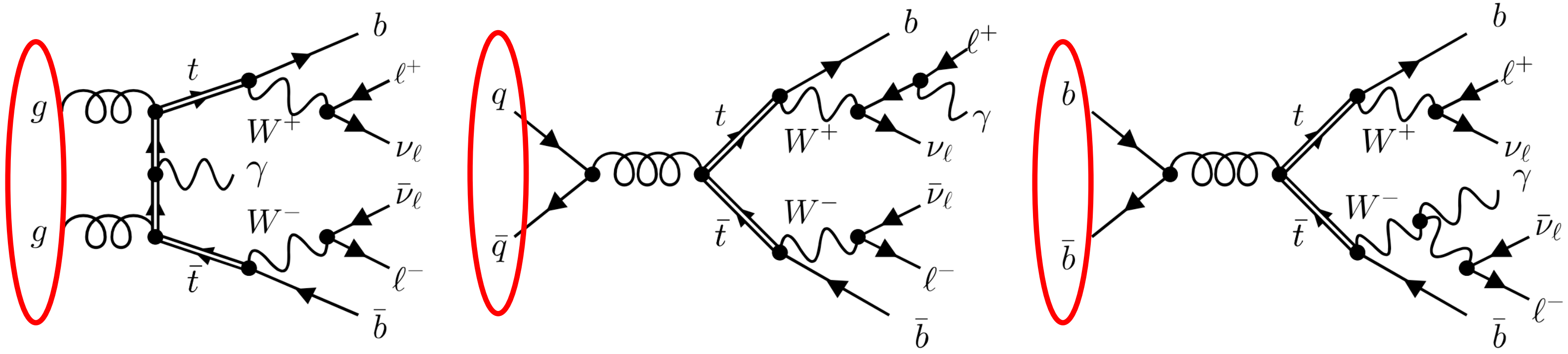
- *Complete NLO predictions in NWA*

Stremmer, Worek e-Print: 2403.03796 [hep-ph]

DEFINITION OF LO$_1$

$pp \to tt\gamma(\gamma)$

- **LO$_1$:** Dominant contributions at $\mathcal{O}(\alpha_s^2\alpha^{4+n_\gamma})$ where n_γ is number of photons appearing in Born-level process



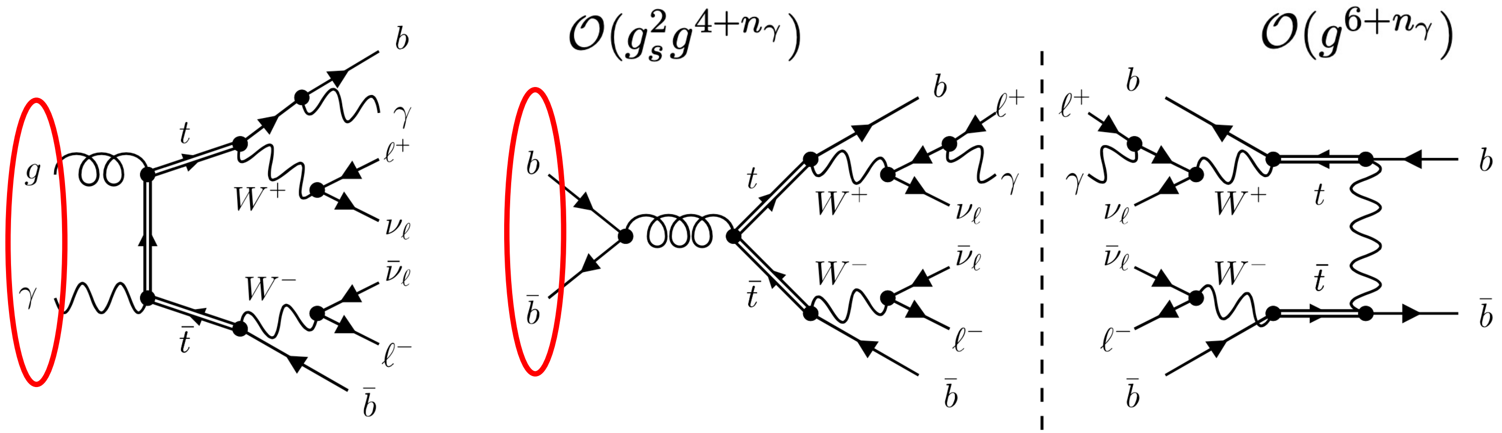
- Typical QCD production of top-quark pair with photons, which leads to the following partonic subprocesses

$gg \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,,$	
$q\bar{q}/\bar{q}q \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,,$	$b\bar{b}/\bar{b}b \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,,$

Definition of LO$_2$

$pp \to tt\gamma(\gamma)$

- **LO$_2$:** Contributions at $\mathcal{O}(\alpha_s^1 \alpha^{5+n_\gamma})$



- Interference between gluon mediated diagrams with Z/γ mediated ones vanishes due to colour for qq initial state $\rightarrow$ Its NLO QCD corrections no longer vanish

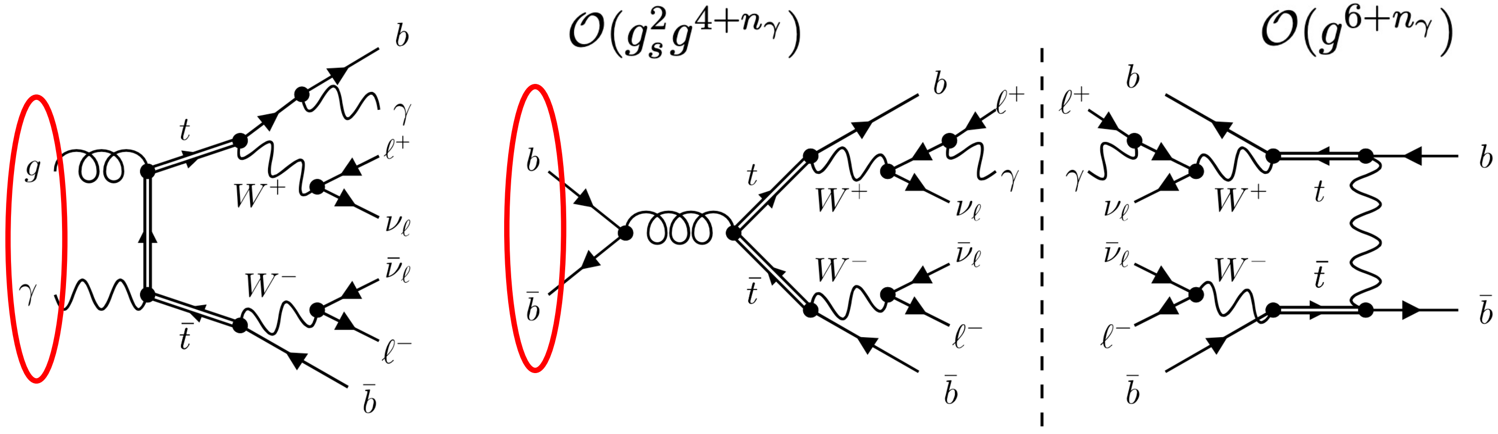
- Interference does not vanish for bb due to t-channel diagrams with intermediate W boson

- When CKM matrix is not diagonal these contributions for qq initial state can also be non-zero but are CKM-suppressed

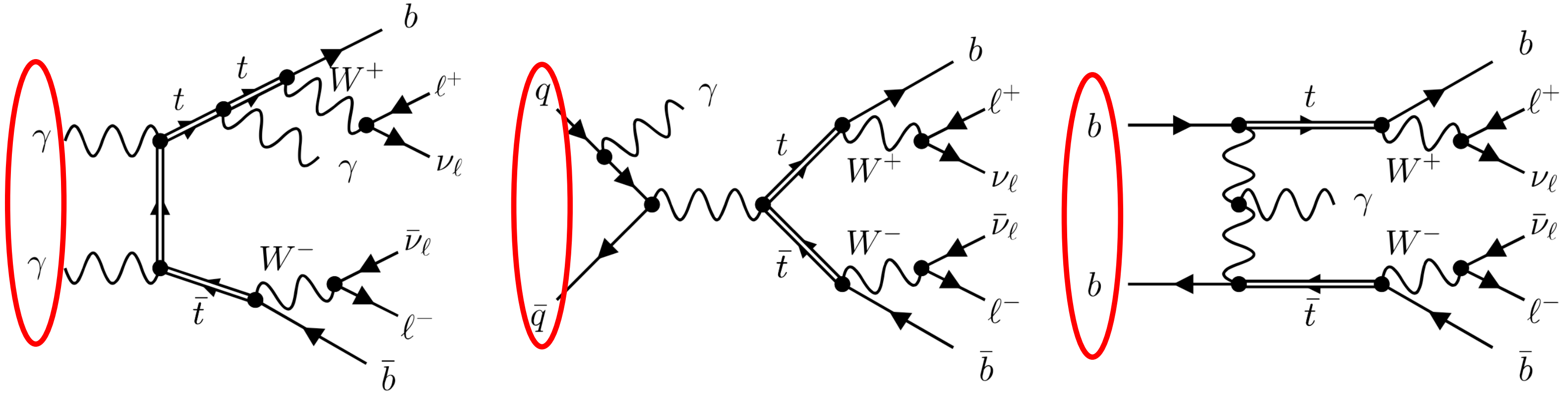
Definition of LO_2 & LO_3

$pp \to tt\gamma(\gamma)$

- **LO_2:** Contributions at $\mathcal{O}(\alpha_s^1 \alpha^{5+n_\gamma})$



- **LO_3:** Purely EW induced production of top-quark pair at $\mathcal{O}(\alpha^{6+n_\gamma})$
  - Suppressed by power coupling & without gluon PDFs



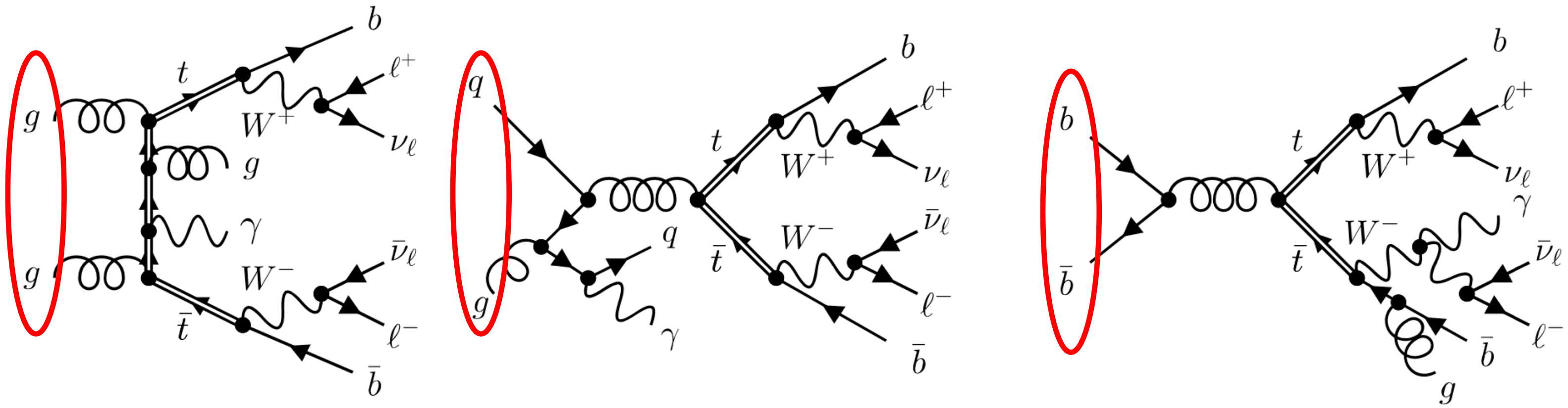
- Interference between gluon mediated diagrams with Z/γ mediated ones vanishes due to colour for qq initial state $\to$ Its NLO QCD corrections no longer vanish
- Interference does not vanish for bb due to t-channel diagrams with intermediate W boson
- When CKM matrix is not diagonal these contributions for qq initial state can also be non-zero but are CKM-suppressed

$$\mathrm{LO} = \mathrm{LO}_1 + \mathrm{LO}_2 + \mathrm{LO}_3$$

Definition of NLO$_1$

$pp \to tt\gamma(\gamma)$

- **NLO$_1$**: Dominant higher-order corrections at NLO arise from QCD corrections to **LO$_1$** at $\mathcal{O}(\alpha_s^3\alpha^{4+n_\gamma})$



- With following partonic subprocesses

$$gg \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,g\,,$$

$$q\bar{q}/\bar{q}q \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,g\,, \qquad b\bar{b}/\bar{b}b \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,g\,,$$

$$gq/qg \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,q\,, \qquad g\bar{q}/\bar{q}g \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,\bar{q}\,,$$

$$gb/bg \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,b\,, \qquad g\bar{b}/\bar{b}g \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,\bar{b}\,.$$

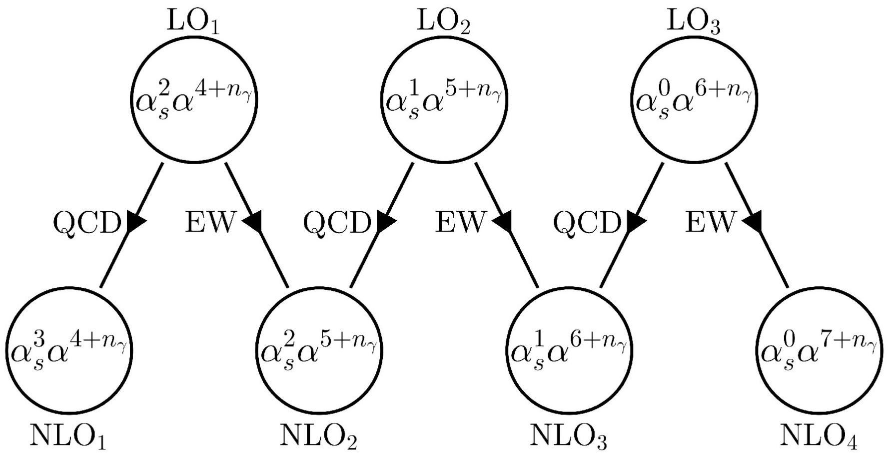
$$\mathrm{NLO_{QCD}} = \mathrm{LO}_1 + \mathrm{NLO}_1$$

Definition of NLO_2 & NLO_3 & NLO_4

$pp \to tt\gamma(\gamma)$

- **NLO_2 & NLO_3:** cannot be completely separated into parts with only QCD or EW corrections

- **NLO_4:** NLO EW corrections to **LO_3**



- **NLO_2 @** $\mathcal{O}(\alpha_s^2\alpha^{5+n_\gamma})$
  - **NLO EW** corrections to **LO_1**
  - **NLO QCD** corrections to **LO_2**

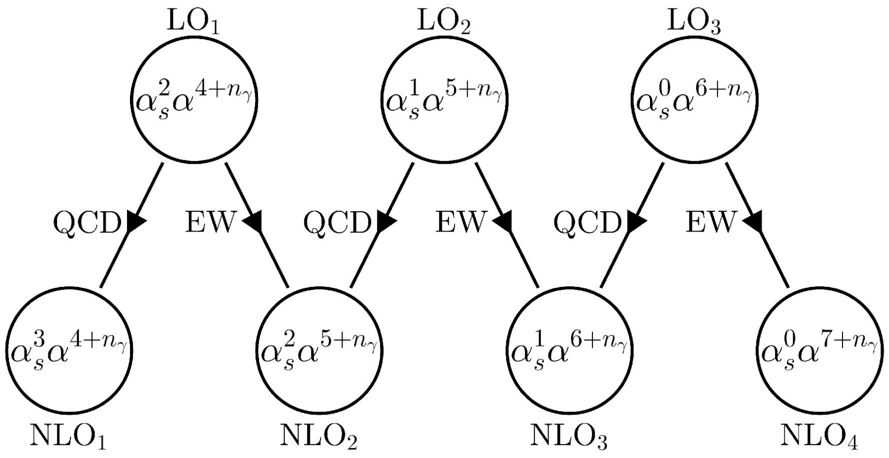
$$\mathrm{NLO} = \mathrm{LO}_1 + \mathrm{LO}_2 + \mathrm{LO}_3 + \mathrm{NLO}_1 + \mathrm{NLO}_2 + \mathrm{NLO}_3 + \mathrm{NLO}_4$$

DEFINITION OF NLO_2 & NLO_3 & NLO_4

$pp \to tt\gamma(\gamma)$

- **NLO_2 & NLO_3:** cannot be completely separated into parts with only QCD or EW corrections

- **NLO_4:** NLO EW corrections to **LO_3**



- **NLO_2 @** $\mathcal{O}(\alpha_s^2\alpha^{5+n_\gamma})$
  - **NLO EW** corrections to **LO_1**
  - **NLO QCD** corrections to **LO_2**

$$\mathrm{NLO}_{\mathrm{QCD+EW}} \equiv \mathrm{LO}_1 + \mathrm{NLO}_1 + \mathrm{NLO}_2$$

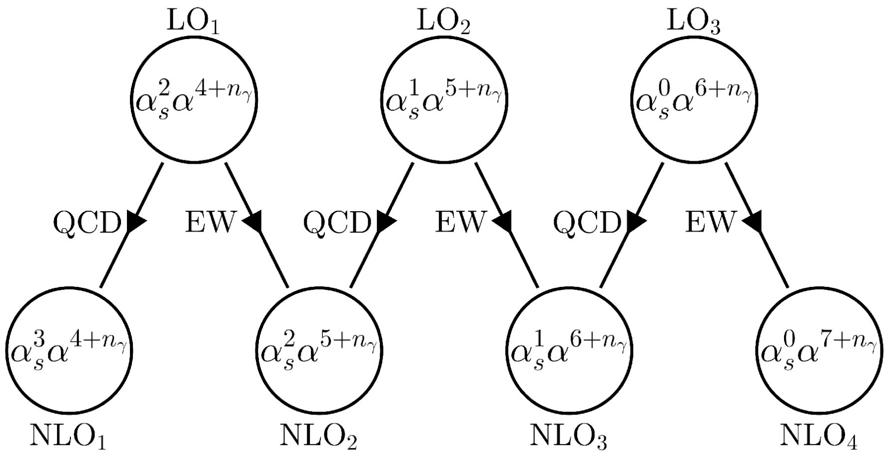
$$\mathrm{NLO} = \mathrm{LO}_1 + \mathrm{LO}_2 + \mathrm{LO}_3 + \mathrm{NLO}_1 + \mathrm{NLO}_2 + \mathrm{NLO}_3 + \mathrm{NLO}_4$$

WE INCLUDE ALL CONTRIBUTIONS

DEFINITION OF NLO_2 & NLO_3 & NLO_4

$pp \to tt\gamma(\gamma)$

- **NLO_2 & NLO_3:** cannot be completely separated into parts with only QCD or EW corrections
- **NLO_4:** NLO EW corrections to **LO_3**



- **NLO_2 @** $\mathcal{O}(\alpha_s^2\alpha^{5+n_\gamma})$
  - **NLO EW** corrections to **LO_1**
  - **NLO QCD** corrections to **LO_2**

$$\mathrm{NLO}_{\mathrm{QCD+EW}} \equiv \mathrm{LO}_1 + \mathrm{NLO}_1 + \mathrm{NLO}_2$$

$$\mathrm{NLO} = \mathrm{LO}_1 + \mathrm{LO}_2 + \mathrm{LO}_3 + \mathrm{NLO}_1 + \mathrm{NLO}_2 + \mathrm{NLO}_3 + \mathrm{NLO}_4$$

WE INCLUDE ALL CONTRIBUTIONS

$$\mathrm{NLO}_{\mathrm{prd}} = \mathrm{LO}_1 + \mathrm{LO}_2 + \mathrm{LO}_3 + \mathrm{NLO}_1 + \mathrm{NLO}_{2,\mathrm{prd}} + \mathrm{NLO}_{3,\mathrm{prd}} + \mathrm{NLO}_{4,\mathrm{prd}}$$

BUT WE ALSO LOOK AT APPROXIMATION

NLO_{prd} $\to$ photon bremsstrahlung & subleading NLO corrections in production only
$\to$ **NLO_2 & NLO_3 & NLO_4** approximated
$\to$ **LO & NLO_1** complete

Computational Framework

$pp \to tt\gamma(\gamma)$

Virtual corrections: HELAC-1LOOP & RECOLA+COLLIER

Actis, Denner, Hofer, Lang, Scharf, Uccirati, Comput. Phys. Commun. 214 (2017) 140
Denner, Lang, Uccirati, Comput. Phys. Commun. 224 (2018) 346

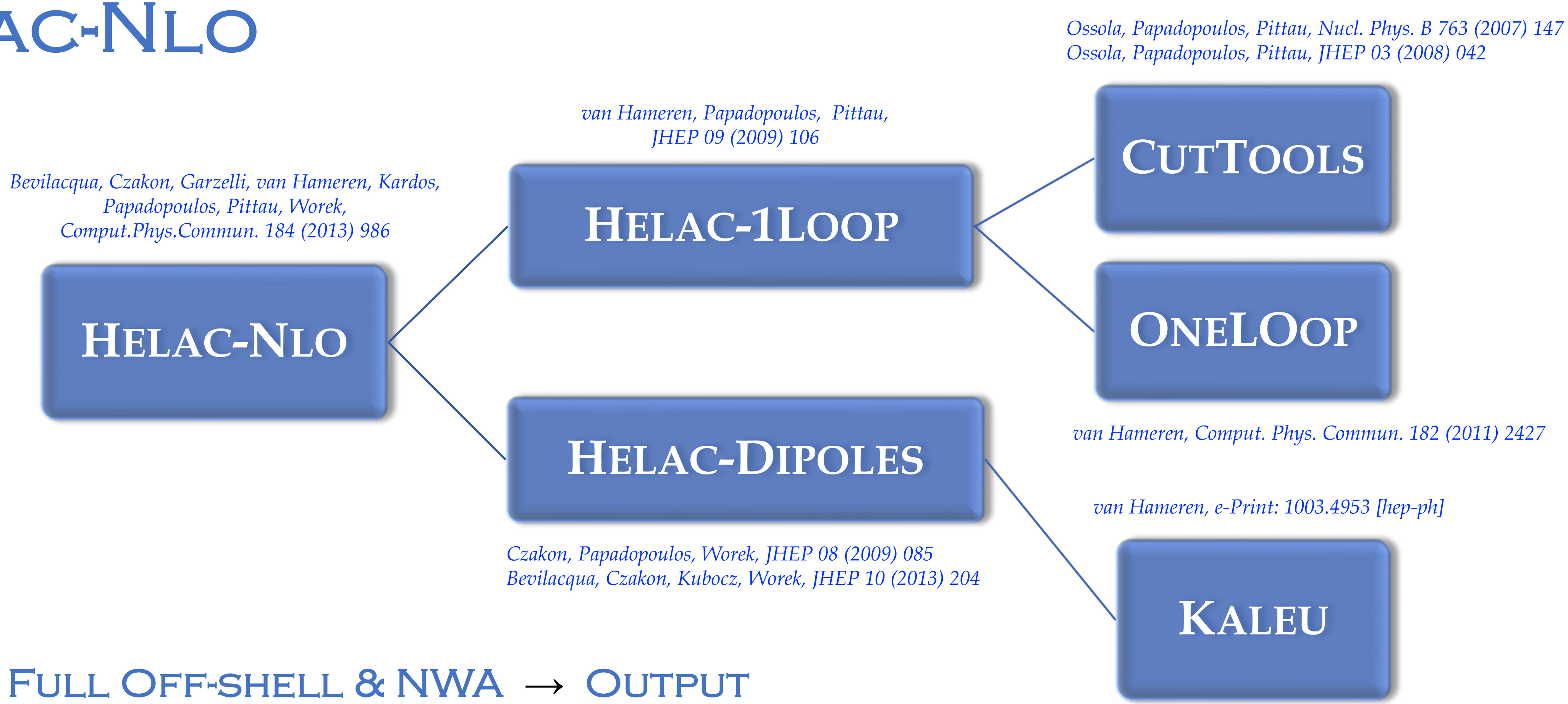
- Modifications in **RECOLA**
  - Partially unweighted events at Born used to calculate 1-loop corrections via reweighting techniques
  - Random polarisation method
  - Reduction to scalar integrals with OPP method with **CUTTOOLS & ONELOOP**

- α^n split into $\alpha_{G_\mu}^{n-n_\gamma}\alpha(0)^{n_\gamma} \longrightarrow n_\gamma = 1 \text{ or } 2$
  - α set to α_{G_μ} first & rescaled $\left(\alpha(0)/\alpha_{G_\mu}\right)^{n_\gamma} \to$ $\sigma_{tt\gamma}$ & $\sigma_{tt\gamma\gamma}$ reduced by *3% & 7%*
  - Renormalisation in mixed scheme
    - ✓ First performed renormalisation of all powers of α in G_μ scheme
    - ✓ Changed for $\alpha(0)^{n_\gamma}$ by introducing new counterterm

Real emission: HELAC-DIPOLES

- Two NLO QCD subtraction schemes: Catani-Seymour & Nagy-Soper
  - Soft and collinear singularities of QCD origin
  - Extended to include soft and collinear singularities of QED origin
  - Extended to perform NLO QCD & EW calculations in NWA $\to$ Internal on-shell resonances

HELAC-NLO



- BOTH FULL OFF-SHELL & NWA → OUTPUT

  - Predictions stored as partially unweighted "events" → *ROOT-Ntuples Files & Les Houches Files*
  - Each "event" provided with supplementary matrix element & PDF information
  - Results for different scale settings & PDF choices by can be obtained by reweighting
  - Different observables and/or binning can be provided + more exclusive cuts → With caveat

Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre, Comput.Phys.Commun. 185 (2014) 1443

LHC Setup

$pp \to tt\gamma(\gamma)$

- Inclusive cuts

- *NLO NNPDF3.1luxQED PDF* $\to$ When both higher-order QCD and EW corrections & γ-initiated subprocesses are considered

- IR-safe *anti-k_T jet algorithm* with *R= 0.4*

- Smooth photon isolation prescription $\to$ Event is rejected unless condition below is fulfilled

S. Frixione, Phys. Lett. B429 (1998) 369

$\sum_i E_{T\,i}\,\Theta(R - R_{\gamma i}) \leq \epsilon_\gamma\, E_{T\,\gamma} \left(\frac{1-\cos(R)}{1-\cos(R_{\gamma j})}\right)^n$	for all $R \leq R_{\gamma j}$ with $R_{\gamma j} = 0.4$ and $\epsilon_\gamma = n = 1$.

- Parameters *n & ϵ_γ* not restricted by any constraints

- Arbitrarily soft radiation inside cone around isolated photon allowed $\to$ Collinear (R $\to$ 0) radiation forbidden $\to$ Collinear splittings associated with fragmentation functions removed $\to$ Fixed cone isolation prescription applied in experimental analyses no longer reproduced

Smooth Photon Isolation Prescription

NLO QCD

$pp \to tt\gamma\gamma$

Stremmer, Worek, JHEP 08 (2023) 179

$n = 1$	$\sigma^{\text{NLO}}_{\text{Full}}$ [fb]
$\epsilon_\gamma = 1.0$	$0.2973(3)^{+1.9\%}_{-5.4\%}$
$\epsilon_\gamma = 0.5$	$0.2832(7)^{+1.5\%}_{-4.2\%}$
$E_{T\,\gamma}\,\epsilon_\gamma = 10$ GeV	$0.2666(8)^{+1.0\%}_{-7.2\%}$

Results for different parameter choices of smooth photon isolation prescription in *l+jets* decay channel

di-lepton decay channel → *3% -- 6%*

- Dependence on n & ϵ_γ parameters is not irrelevant
- Could affect comparisons between theoretical predictions and experimental results
- Cross section is reduced by about *5% -- 10%*
- Substantial differences due to high number of jets (up to 5) and/or photons (2)
- Differences similar in size or even larger than corresponding NLO scale uncertainties for this process

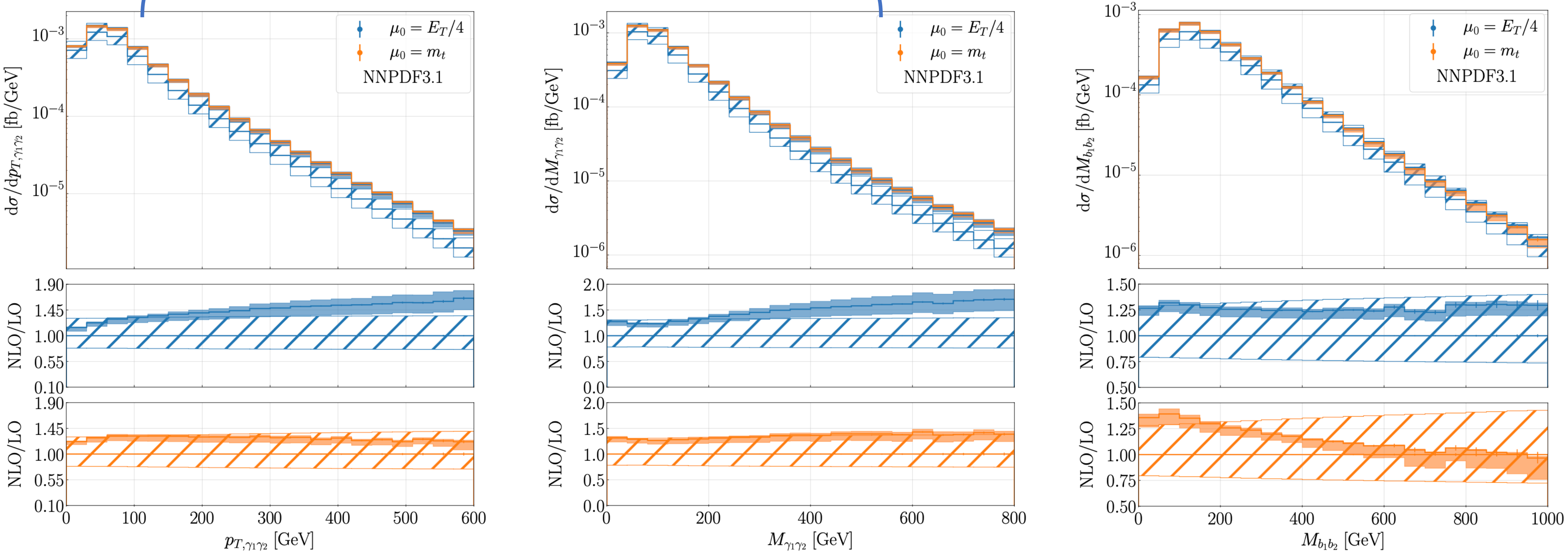
Differential Cross Sections @ NLO_{QCD}

di-lepton

Background to $pp \to ttH \to tt\gamma\gamma$

NLO QCD

$pp \to tt\gamma\gamma$



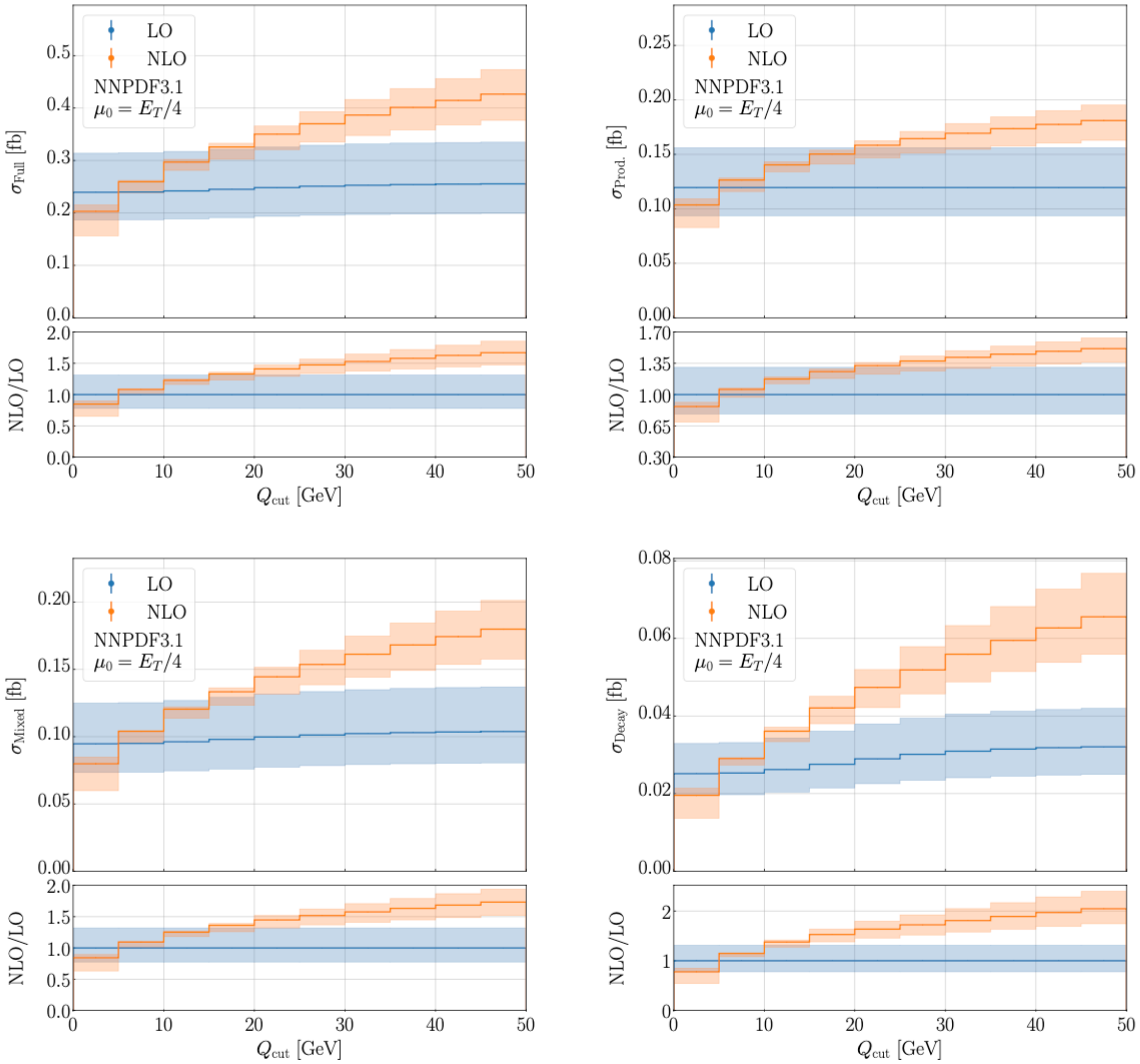
Stremmer, Worek, JHEP 08 (2023) 179

- Results for *¼ E_T (blue)* & *m_t (orange)* @ *NLO (solid) & LO (dashed)*
- Impact of NLO QCD effects on differential distributions substantial
- Higher-order corrections & uncertainties depends on observable & $\boldsymbol{\mu_0}$

Integrated Cross Sections @ NLO$_{QCD}$

l+jets

Stremmer, Worek, JHEP 08 (2023) 179



NLO QCD

$pp \to tt\gamma\gamma$

- Integrated fiducial cross sections @ LO & NLO QCD as function of Q_{cut} parameter in range of $Q_{cut} \in (5 - 50)\ GeV$ in steps of $5\ GeV$

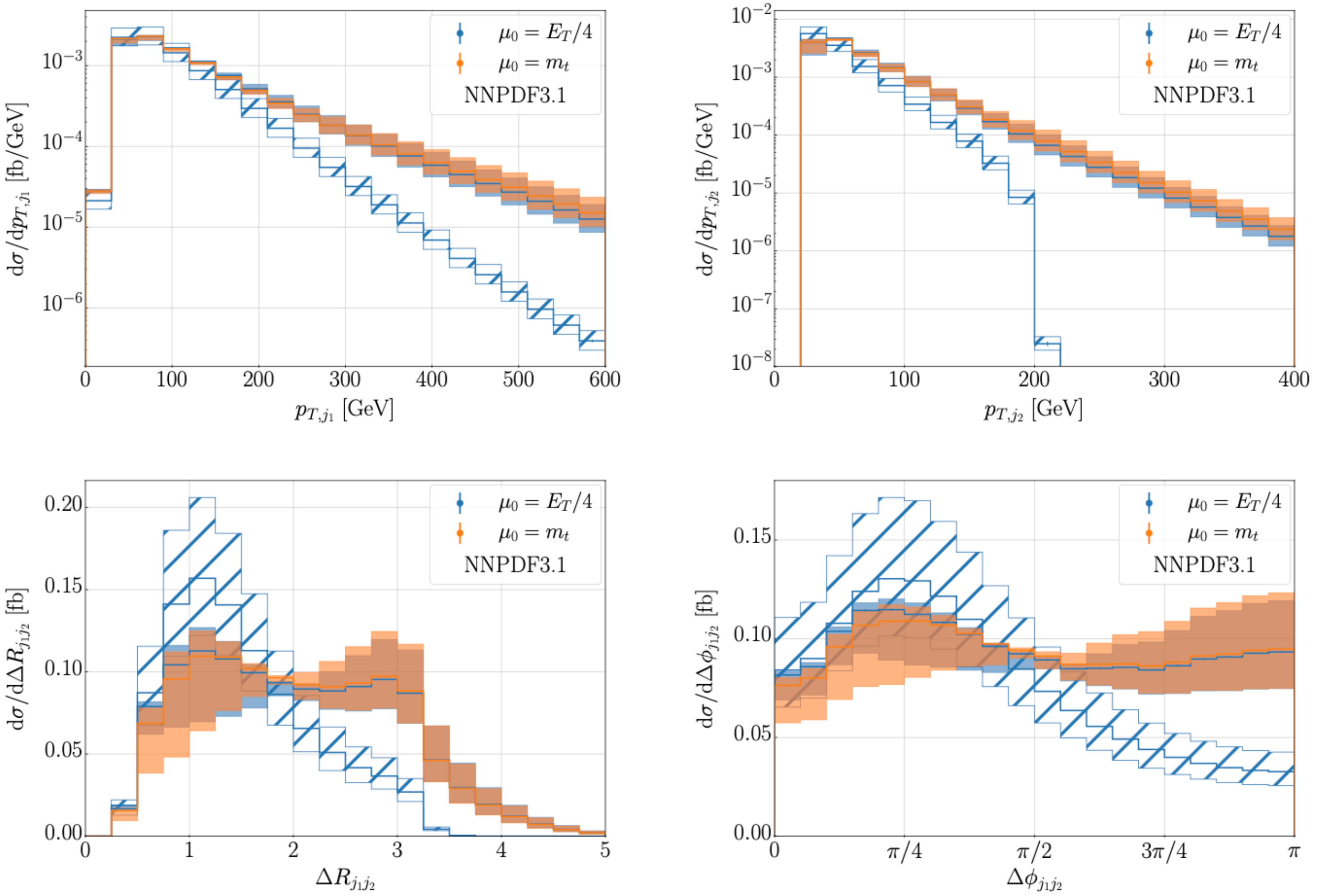
$$|m_W - M_{jj}| < Q_{cut}$$

- Results are shown for full process & Prod., Mixed & Decay
- Differences between two extreme cases $Q_{cut} = 5\ GeV$ & no cut $Q_{cut} \to \infty$ is 7% @ LO
- NLO QCD corrections 67% for $Q_{cut} = 50\ GeV$
- Up to 140% if $Q_{cut} \to \infty$
- We use $|m_W - M_{jj}| < Q_{cut} = 15$ GeV

Differential Cross Sections @ NLO_{QCD}

l+jets

Stremmer, Worek, JHEP 08 (2023) 179



NLO QCD $pp \to tt\gamma\gamma$

$|m_W - M_{jj}| < Q_{cut} = 15$ GeV

- No ratio plots are provided due to extreme values in *K-factors*
- LO phase space of 2 jets restricted due to production mechanism → originate from *W*
- @ NLO QCD jet can also be produced in *tt* production stage
- This jet that is not affected by kinematical restriction can lead to huge enhancements in p_T tails

- Results for *¼ E_T (blue)* & *m_t (orange)* @ *NLO (solid) & LO (dashed)*
- Impact of NLO QCD effects on differential distributions tremendous
- Higher-order corrections & uncertainties depends on observable & μ_0

Distribution of Photons @ $\mathrm{NLO_{QCD}}$

NLO QCD

$pp \to tt\gamma$

di-lepton

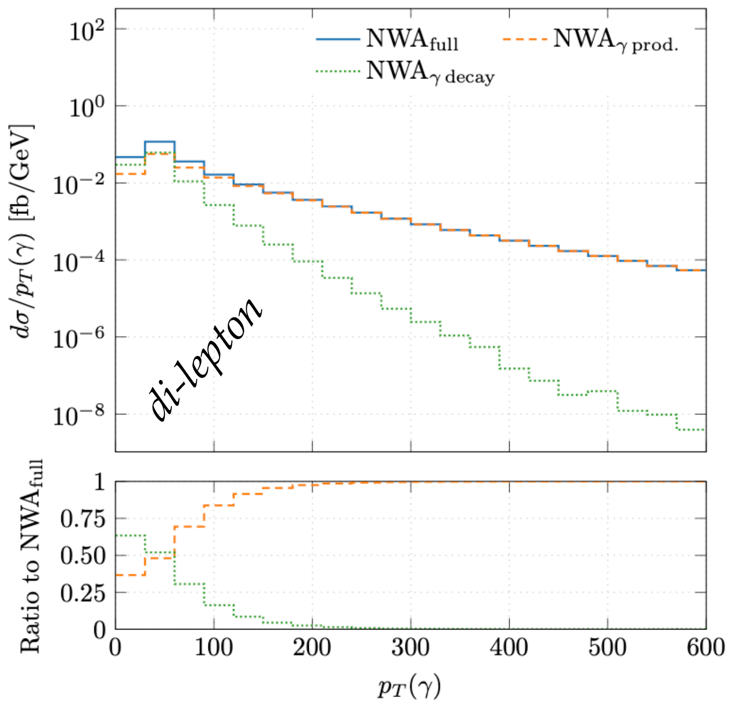
Production

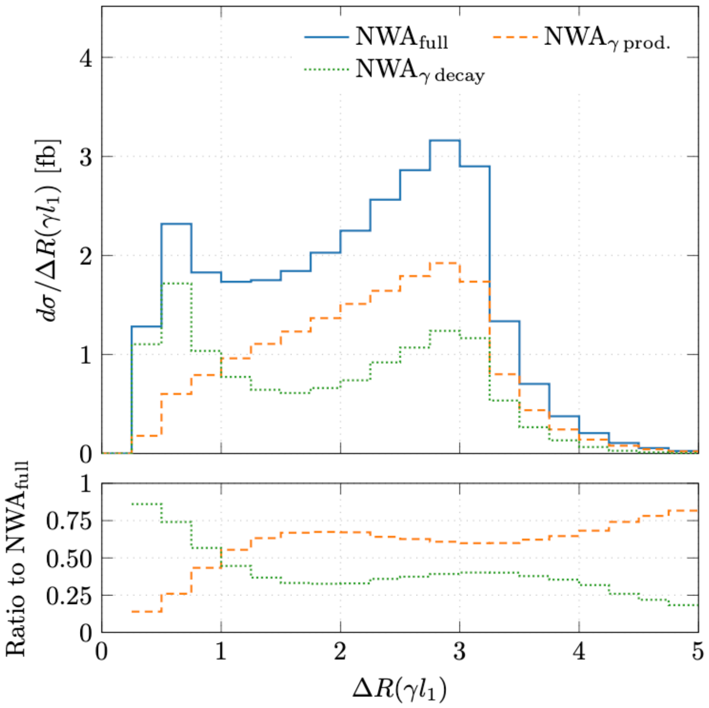
$$d\sigma^{\mathrm{NWA}}_{t\bar{t}\gamma} = d\sigma_{t\bar{t}\gamma}\, d\mathcal{B}_{t\to be^+\nu_e}\, d\mathcal{B}_{\bar{t}\to \bar{b}\mu^-\bar{\nu}_\mu}$$

Decays

$$+\, d\sigma_{t\bar{t}} \left(d\mathcal{B}_{t\to be^+\nu_e\gamma}\, d\mathcal{B}_{\bar{t}\to \bar{b}\mu^-\bar{\nu}_\mu} + d\mathcal{B}_{t\to be^+\nu_e}\, d\mathcal{B}_{\bar{t}\to \bar{b}\mu^-\bar{\nu}_\mu\gamma} \right)$$

- Photon radiation in production & decays
- Integrated level @ NLO QCD
  - $p_{Tb} > 40$ GeV, $p_{T\gamma} > 25$ GeV
  - *Prod. contribution* $\to$ *57%*
  - *Decay contribution* $\to$ *43%*
  - With $p_{Tb} > 25$ GeV $\to$ *50% - 50%*
- Differential level @ NLO QCD
  - Various phase-space regions with various effects





Bevilacqua, Hartanto, Kraus, Weber, Worek, JHEP 03 (2020) 154

Distribution of Photons @ NLO$_{\text{QCD}}$

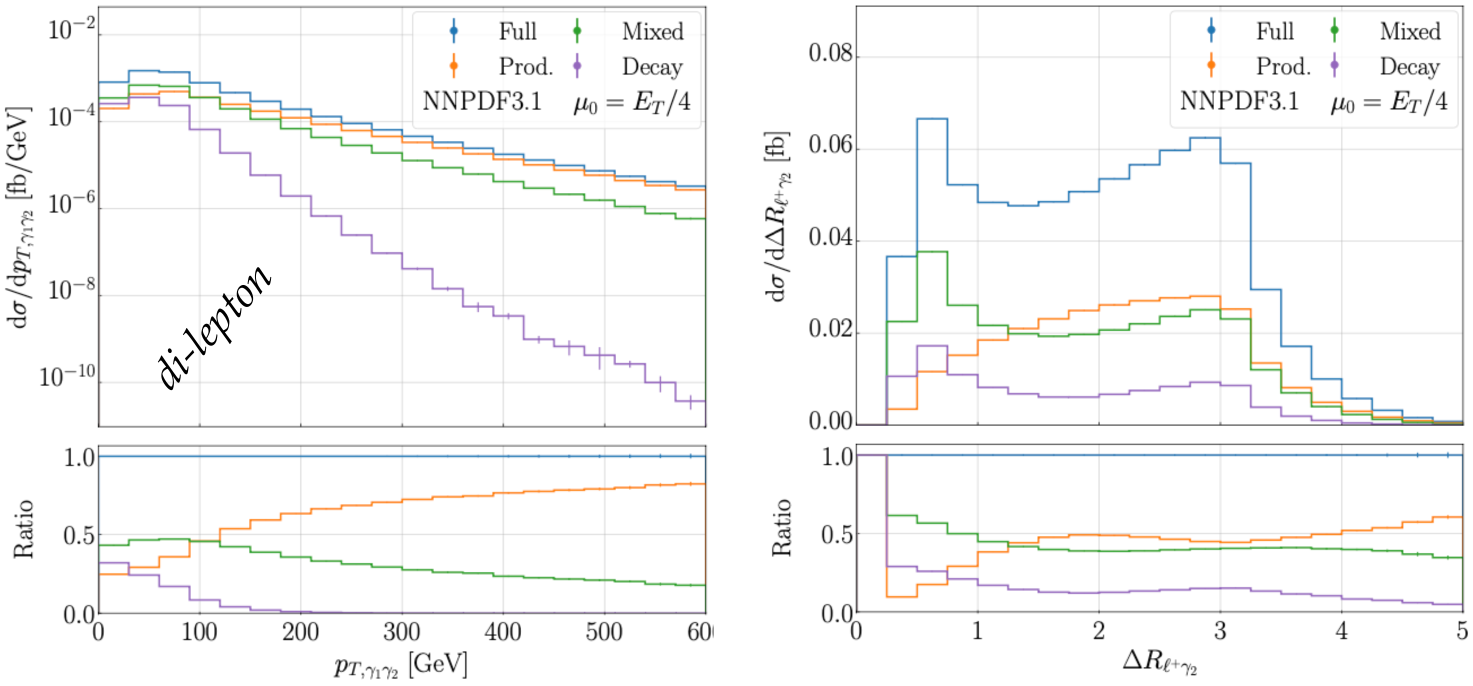
NLO QCD

$pp \to tt\gamma\gamma$

di-lepton

- Photon radiation in production & decays
- **Integrated level @ NLO QCD**
  - $p_{Tb} > 25$ GeV, $p_{T\gamma} > 25$ GeV
  - *Mixed contribution → 44%*
  - *Prod. contribution → 40%*
  - *Decay contribution → 16%*
- **Differential level @ NLO QCD**
  - Various phase-space regions with various effects

$$d\sigma_{\text{Full}} = \overbrace{d\sigma_{t\bar{t}\gamma\gamma} \times \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t}}^{\sigma_{\text{Prod.}}} + \overbrace{d\sigma_{t\bar{t}\gamma} \times \left(\frac{d\Gamma_{t\gamma}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t} + \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}\gamma}}{\Gamma_t} \right)}^{\sigma_{\text{Mixed}}}$$
$$\underbrace{+ d\sigma_{t\bar{t}} \times \left(\frac{d\Gamma_{t\gamma\gamma}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t} + \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}\gamma\gamma}}{\Gamma_t} + \frac{d\Gamma_{t\gamma}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}\gamma}}{\Gamma_t} \right)}_{\sigma_{\text{Decay}}} .$$



Stremmer, Worek, JHEP 08 (2023) 179

Distribution of Photons @ NLO_{QCD}

NLO QCD

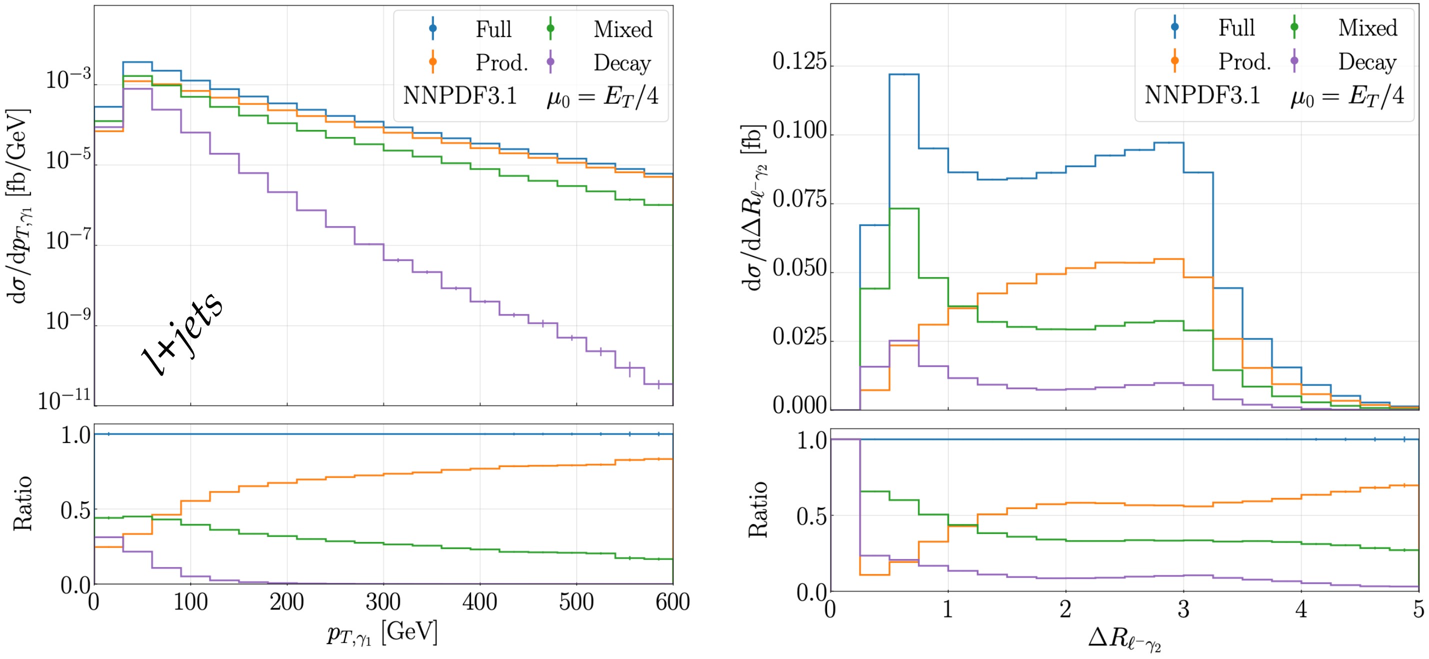
$pp \to tt\gamma\gamma$

l+jets

$$d\sigma_{\text{Full}} = \overbrace{d\sigma_{t\bar{t}\gamma\gamma} \times \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t}}^{\sigma_{\text{Prod.}}} + \overbrace{d\sigma_{t\bar{t}\gamma} \times \left(\frac{d\Gamma_{t\gamma}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t} + \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}\gamma}}{\Gamma_t} \right)}^{\sigma_{\text{Mixed}}}$$

$$\underbrace{+ d\sigma_{t\bar{t}} \times \left(\frac{d\Gamma_{t\gamma\gamma}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t} + \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}\gamma\gamma}}{\Gamma_t} + \frac{d\Gamma_{t\gamma}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}\gamma}}{\Gamma_t} \right)}_{\sigma_{\text{Decay}}} .$$

- Photon radiation in production & decays
- **Integrated level @ NLO QCD** with & without $|m_W - M_{jj}| < Q_{cut} = 15$ GeV
  - $p_{Tb} > 25$ GeV, $p_{Tj} > 25$ GeV, $p_{T\gamma} > 25$ GeV
  - *Prod. contribution → 48% → 40%*
  - *Mixed contribution → 40% → 43%*
  - *Decay contribution → 12% → 17%*
- **Differential level @ NLO QCD**
  - Various phase-space regions with various effects



Stremmer, Worek, JHEP 08 (2023) 179

NLO_{QCD} & NLO_{PRD} & NLO

Complete NLO | $pp \to t\bar{t}\gamma$ | *di-lepton*

- Differences between **LO_1 & LO** below *1%*
- Differences between **NLO_{QCD} & NLO** below *1%*
- Differences between **NLO_{prd} & NLO** below *1%*

		σ_i [fb]	Ratio to LO_1
LO_1	$\mathcal{O}(\alpha_s^2\alpha^5)$	$55.604(8)^{+31.4\%}_{-22.3\%}$	1.00
LO_2	$\mathcal{O}(\alpha_s^1\alpha^6)$	$0.18775(5)^{+20.1\%}_{-15.4\%}$	+0.34%
LO_3	$\mathcal{O}(\alpha_s^0\alpha^7)$	$0.26970(4)^{+14.3\%}_{-16.9\%}$	+0.49%
NLO_1	$\mathcal{O}(\alpha_s^3\alpha^5)$	+3.44(5)	+6.19%
NLO_2	$\mathcal{O}(\alpha_s^2\alpha^6)$	−0.1553(9)	−0.28%
NLO_3	$\mathcal{O}(\alpha_s^1\alpha^7)$	+0.2339(3)	+0.42%
NLO_4	$\mathcal{O}(\alpha_s^0\alpha^8)$	+0.001595(8)	+0.003%
LO		$56.061(8)^{+31.2\%}_{-22.1\%}$	1.0082
NLO_{QCD}		$59.05(5)^{+1.6\%}_{-5.9\%}$	1.0620
NLO_{prd}		$59.08(5)^{+1.5\%}_{-5.9\%}$	1.0626
NLO		$59.59(5)^{+1.6\%}_{-5.9\%}$	1.0717

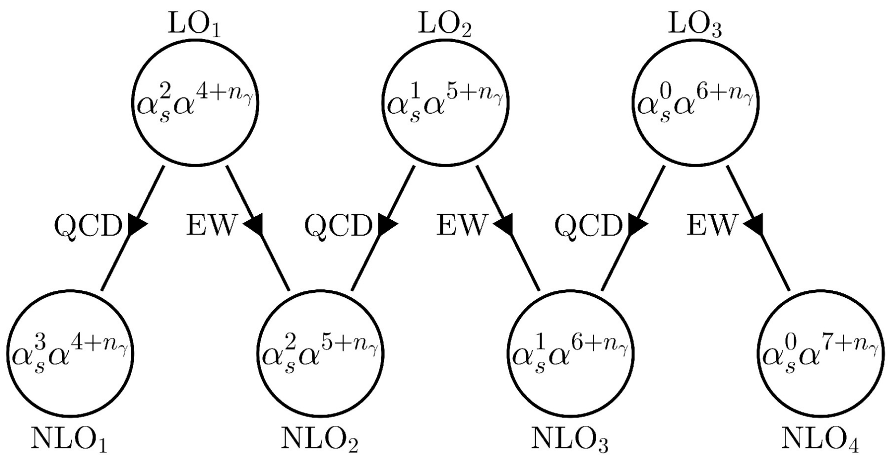
Stremmer, Worek e-Print: 2403.03796 [hep-ph]

$$\text{LO} = \text{LO}_1 + \text{LO}_2 + \text{LO}_3$$

$$\text{NLO}_{\text{QCD}} = \text{LO}_1 + \text{NLO}_1$$

$$\text{NLO} = \text{LO}_1 + \text{LO}_2 + \text{LO}_3 + \text{NLO}_1 + \text{NLO}_2 + \text{NLO}_3 + \text{NLO}_4$$

$$\text{NLO}_{\text{prd}} = \text{LO}_1 + \text{LO}_2 + \text{LO}_3 + \text{NLO}_1 + \text{NLO}_{2,\text{prd}} + \text{NLO}_{3,\text{prd}} + \text{NLO}_{4,\text{prd}}$$



NLO_{prd} → photon bremsstrahlung & subleading NLO corrections in production only
→ **NLO_2 & NLO_3 & NLO_4** approximated
→ **LO & NLO_1** complete

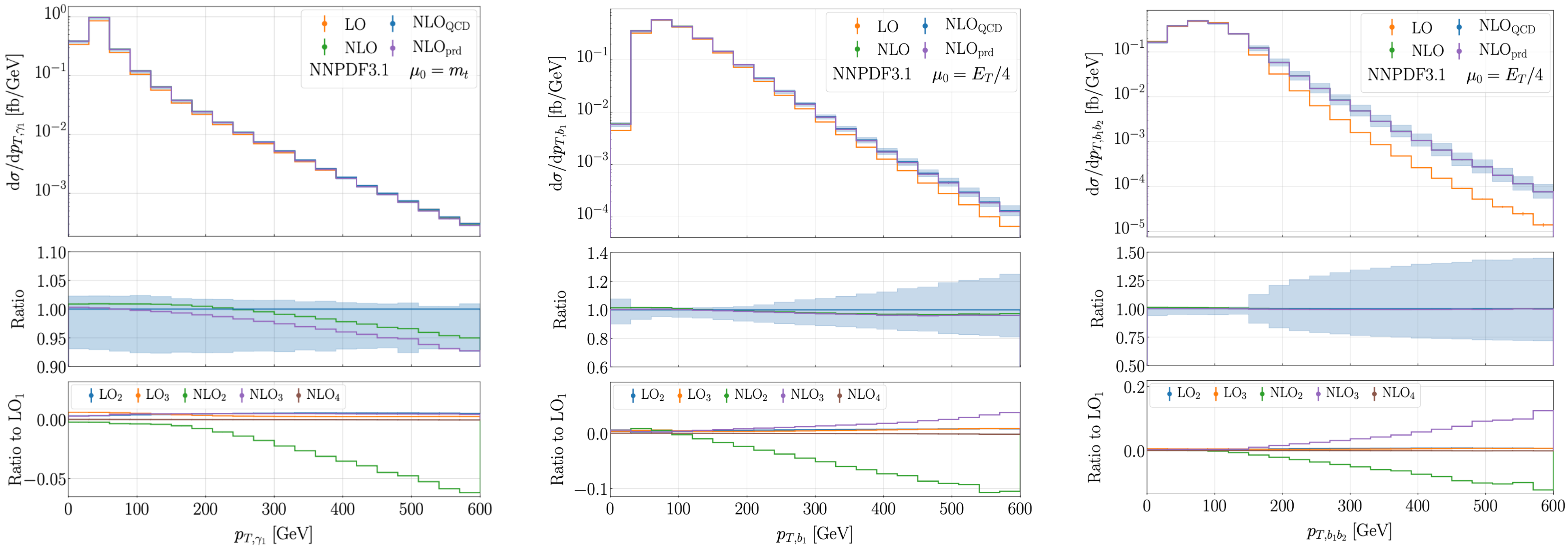
NLO_{QCD} & NLO_{PRD} & NLO

Complete NLO

$pp \to t\bar{t}\gamma$

di-lepton

Stremmer, Worek e-Print: 2403.03796 [hep-ph]

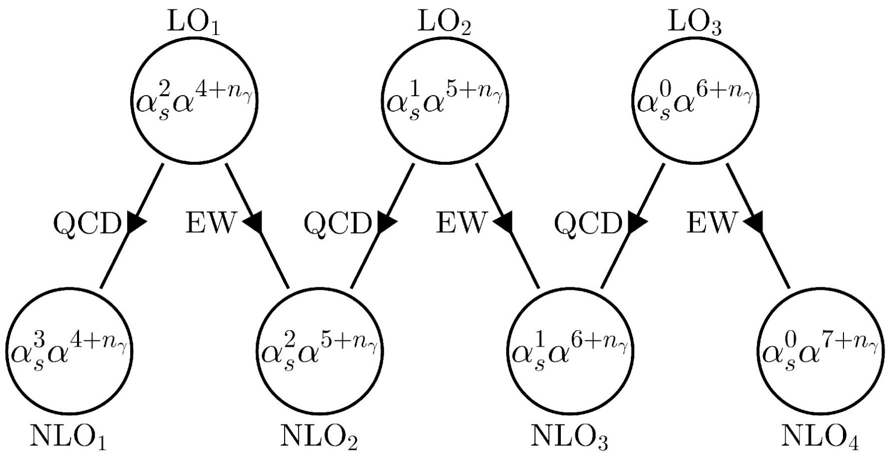


- EW Sudakov logarithms in **NLO_2** leads to reduction in tails of up to *10%* compared to **NLO_{QCD}** result
- Accidental cancellations between **NLO_2 & NLO_3** $\rightarrow$ Should be considered together
- **NLO_{prd}** approximation models complete **NLO** result very well

$\mathrm{NLO_{QCD}}$ & $\mathrm{NLO_{PRD}}$ & NLO

Complete NLO | $pp \to t\bar{t}\gamma\gamma$ | *di-lepton*

$\mathrm{LO} = \mathrm{LO}_1 + \mathrm{LO}_2 + \mathrm{LO}_3$
$\mathrm{NLO_{QCD}} = \mathrm{LO}_1 + \mathrm{NLO}_1$
$\mathrm{NLO} = \mathrm{LO}_1 + \mathrm{LO}_2 + \mathrm{LO}_3 + \mathrm{NLO}_1 + \mathrm{NLO}_2 + \mathrm{NLO}_3 + \mathrm{NLO}_4$
$\mathrm{NLO_{prd}} = \mathrm{LO}_1 + \mathrm{LO}_2 + \mathrm{LO}_3 + \mathrm{NLO}_1 + \mathrm{NLO}_{2,\mathrm{prd}} + \mathrm{NLO}_{3,\mathrm{prd}} + \mathrm{NLO}_{4,\mathrm{prd}}$



$\mathrm{NLO_{prd}}$ → photon bremsstrahlung & subleading NLO corrections in production only
→ **NLO_2 & NLO_3 & NLO_4** approximated
→ **LO & NLO_1** complete

- Differences between LO_1 & LO below *1%*
- Differences between $\mathrm{NLO_{QCD}}$ & NLO below *1%*
- Differences between $\mathrm{NLO_{prd}}$ & NLO below *1%*

		σ_i [fb]	Ratio to LO_1
LO_1	$\mathcal{O}(\alpha_s^2\alpha^6)$	$0.15928(3)^{+31.3\%}_{-22.1\%}$	1.00
LO_2	$\mathcal{O}(\alpha_s^1\alpha^7)$	$0.0003798(2)^{+25.8\%}_{-19.2\%}$	+0.24%
LO_3	$\mathcal{O}(\alpha_s^0\alpha^8)$	$0.0010991(2)^{+10.6\%}_{-13.1\%}$	+0.69%
NLO_1	$\mathcal{O}(\alpha_s^3\alpha^6)$	+0.0110(2)	+6.89%
NLO_2	$\mathcal{O}(\alpha_s^2\alpha^7)$	−0.00233(2)	−1.46%
NLO_3	$\mathcal{O}(\alpha_s^1\alpha^8)$	+0.000619(1)	+0.39%
NLO_4	$\mathcal{O}(\alpha_s^0\alpha^9)$	−0.0000166(2)	−0.01%
LO		$0.16076(3)^{+30.9\%}_{-21.9\%}$	1.0093
$\mathrm{NLO_{QCD}}$		$0.1703(2)^{+1.9\%}_{-6.2\%}$	1.0690
$\mathrm{NLO_{prd}}$		$0.1694(2)^{+1.7\%}_{-5.9\%}$	1.0637
NLO		$0.1700(2)^{+1.8\%}_{-6.0\%}$	1.0674

Stremmer, Worek e-Print: 2403.03796 [hep-ph]

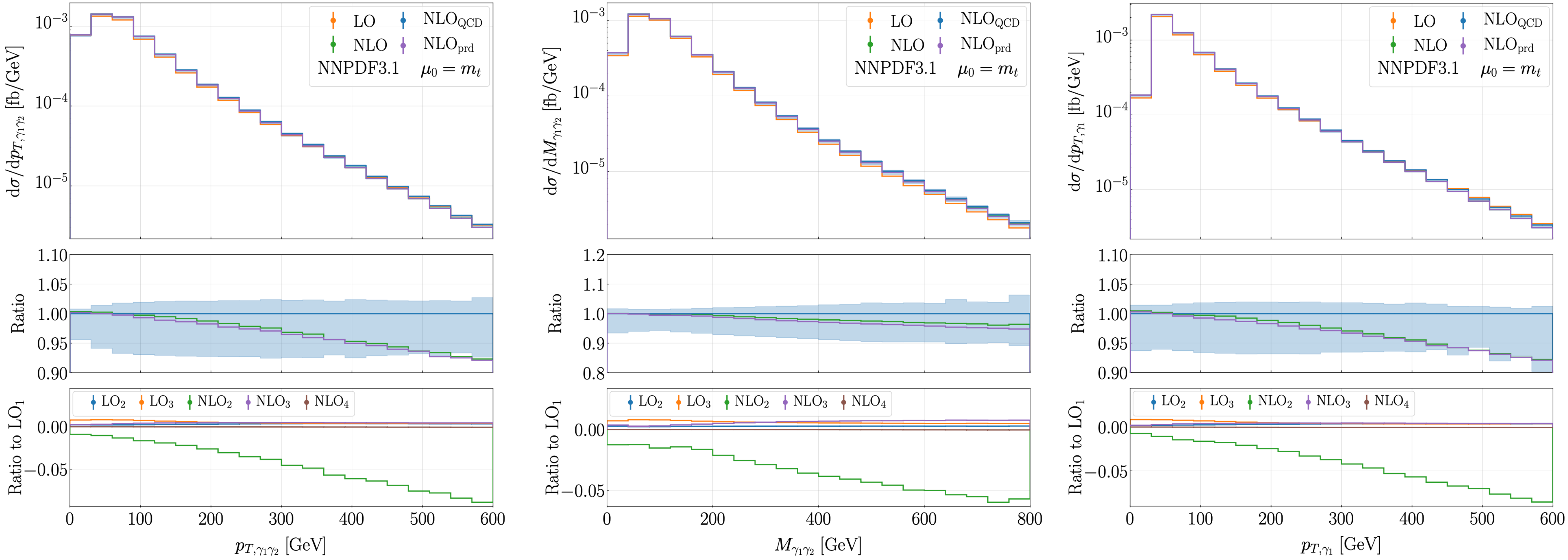
NLO_{QCD} & NLO_{PRD} & NLO

Complete NLO

$pp \to tt\gamma\gamma$

di-lepton

Background to $pp \to ttH \to tt\gamma\gamma$



Stremmer, Worek e-Print: 2403.03796 [hep-ph]

- **NLO_2** can be as large as **NLO_{QCD}** scale uncertainties
- Potentially affecting comparison between theory & experiment

SUMMARY

- Impact of **NLO QCD** effects on differential distributions substantial
- Size of higher-order corrections & uncertainties depends on observable & scale choice
- Photon emission from all charged particles important
- EW Sudakov logarithms in **NLO_2** leads to reduction in tails of up to *10%* compared to **NLO_{QCD}** result
- Accidental cancellations between **NLO_2 & NLO_3** $\rightarrow$ Should be considered together
- **NLO_{prd}** approximation models complete **NLO** result very well
- **NLO_2** can be as large as **NLO_{QCD}** scale uncertainties $\rightarrow$ Potentially affecting comparison between theory & experiment