Research Training Group Physics of the Heaviest Particles at the LHC | 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

Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

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*
  - Modelling of unstable top quarks and W bosons → *NWA*
  - *NLO QCD* → QCD corrections & photon radiation in production & decays
  - *Complete NLO* → QCD & EW corrections & photon radiation in production & decays

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

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

- NLO QCD results for *$pp \to tt\gamma\gamma$*
  - Results in NWA available also for *l+jets* decay channel

Stremmer, Worek, JHEP 08 (2023) 179

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
  - Within current uncertainties differential cross-section distributions described suficently 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 $pp \to tt\gamma\gamma$ 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

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 $\to$ 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

$pp \to tt\gamma\gamma$

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

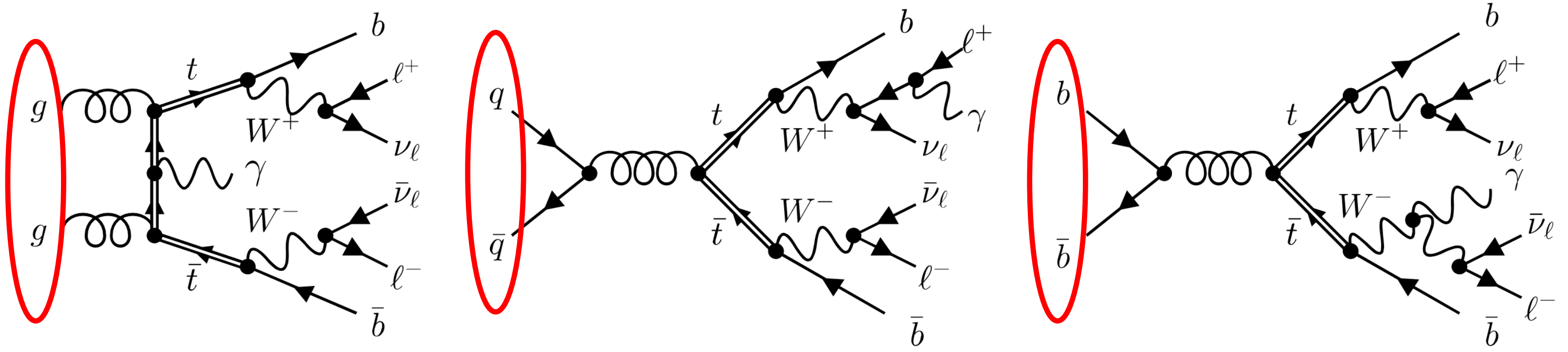
Stremmer, Worek, JHEP 08 (2023) 179

- *Complete NLO predictions in NWA*

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

LO_1

- **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

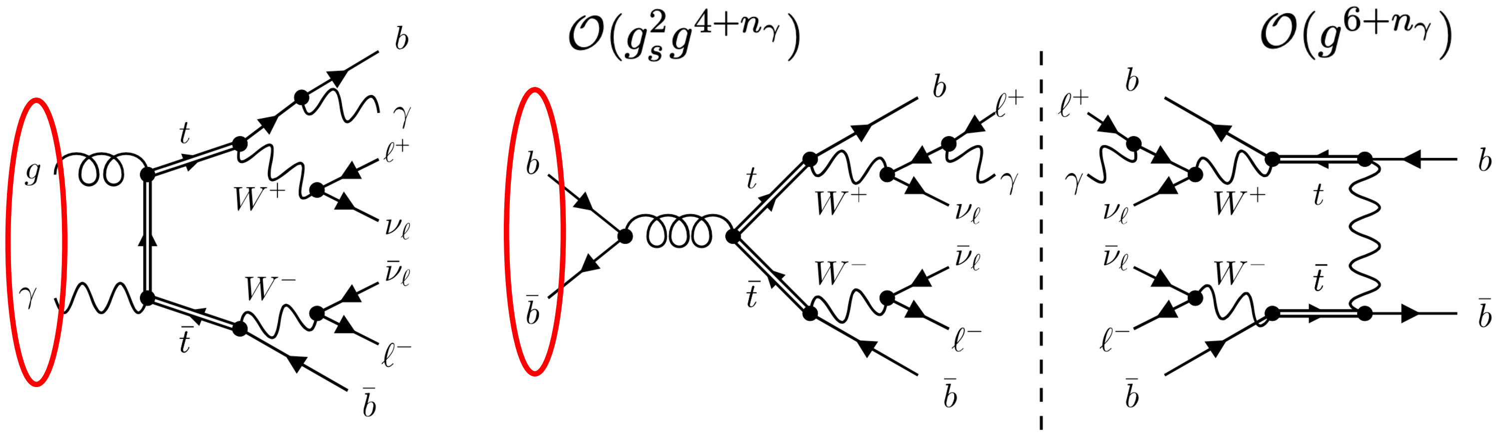


- Typical QCD production of top-quark pair with photons, which leads to the following partonic subprocesses

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

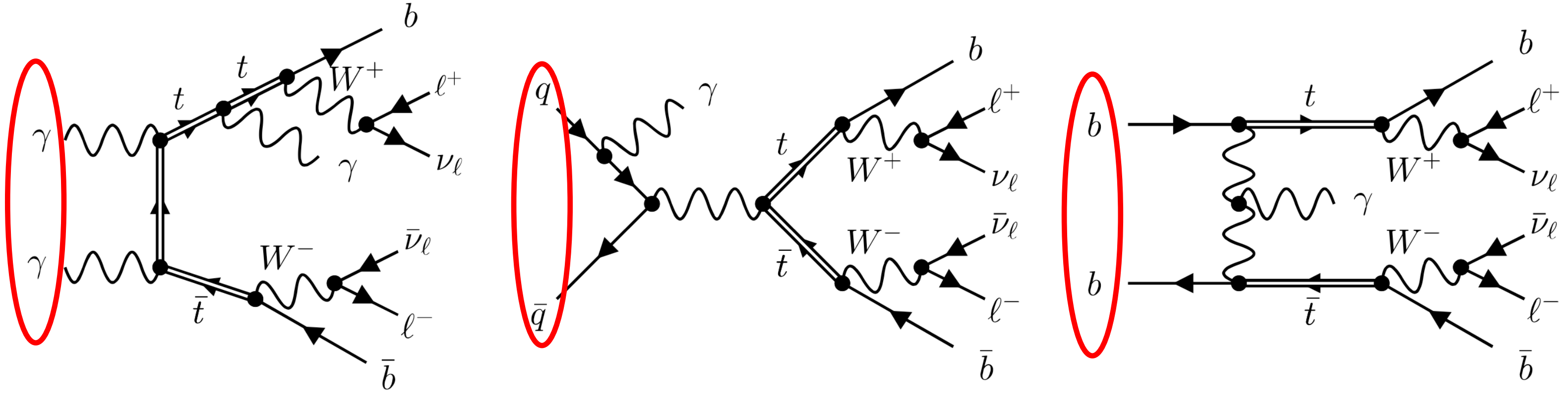
LO_2 & LO_3

- **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 & gluon PDF does not enter this contribution at all



- Interference between gluon mediated diagrams with Z/γ mediated ones vanishes due to colour for qq initial state

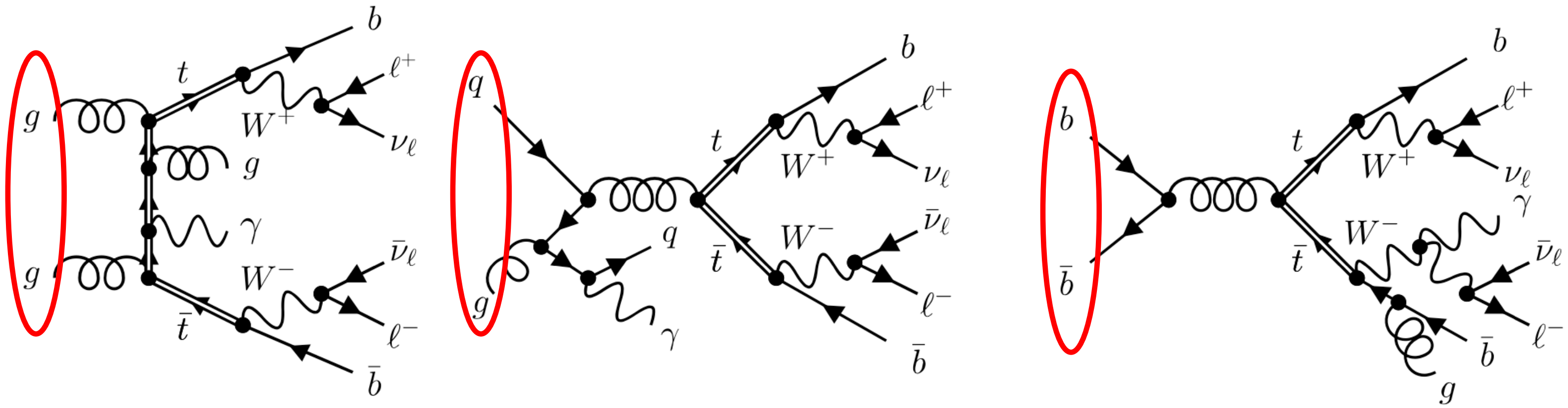
- Interference does not vanish for bb due to t-channel diagrams with intermediate W boson

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

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

NLO_1

- **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

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

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

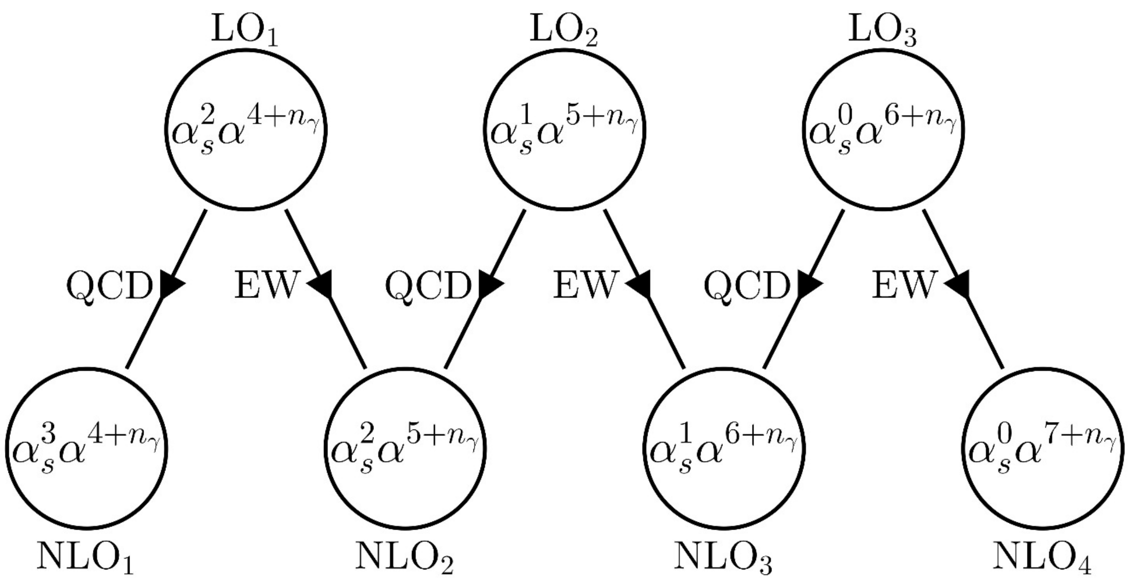
$$q\bar{q}/\bar{q}q \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,g\,, \qquad b\bar{b}/\bar{b}b \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,g\,,$$

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

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

NLO_2 & NLO_3 & NLO_4

- **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**

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

WE INCLUDE ALL CONTRIBUTIONS

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

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

Computational Framework

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

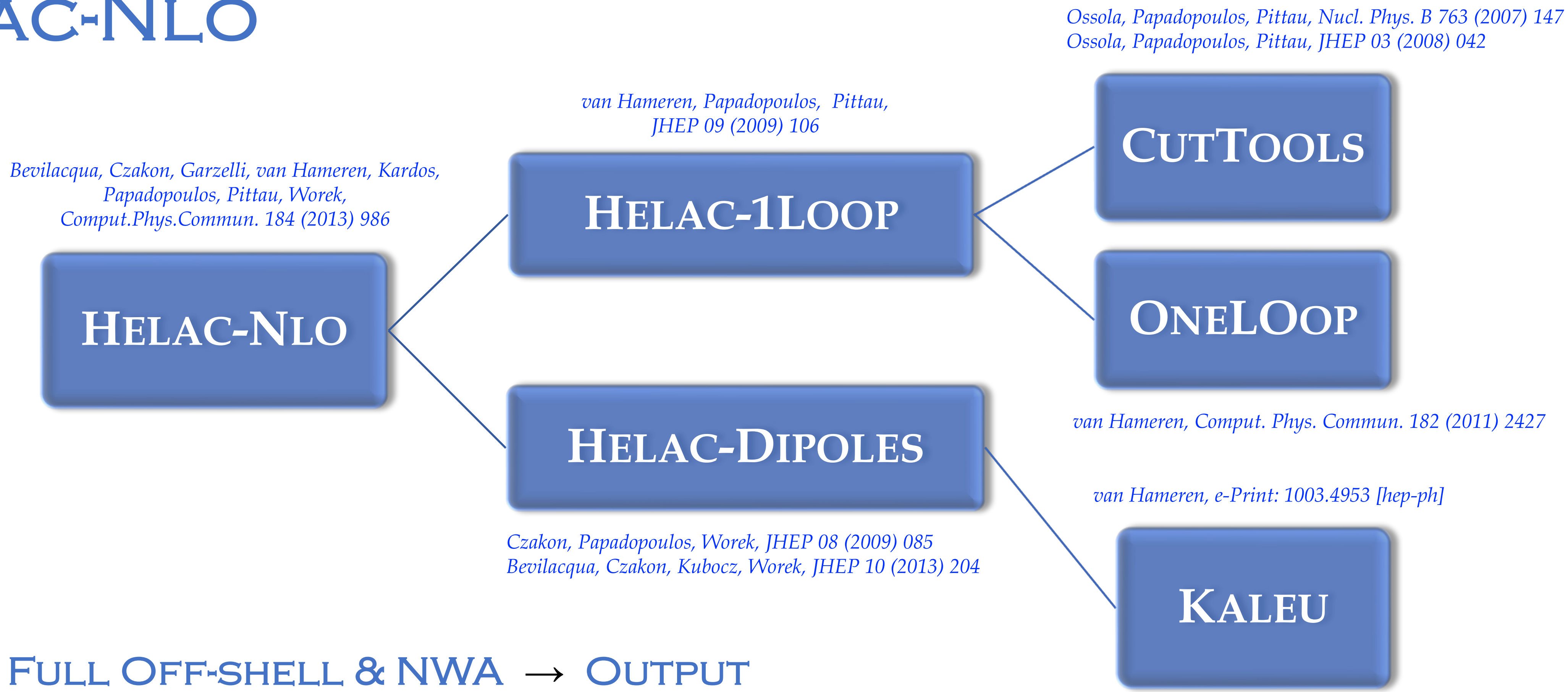
- Modifications in **RECOLA**
  - Partially unweighted events at Born used to calculate 1-loop corrections via reweighting techniques
  - Random polarisation method
  - Reduction to scalar integrals with OPP method with **CUTTOOLS & ONELOOP**

- α^n split into $\alpha_{G_\mu}^{n-n_\gamma}\alpha(0)^{n_\gamma} \;\rightarrow\; n_\gamma = 1 \; (n_\gamma = 2)$
  - In calculation α^n set to $\alpha = \alpha_{G_\mu}$ first & rescaled $(\alpha(0)/\alpha_{G_\mu})^{n_\gamma} \rightarrow$ $\boldsymbol{\sigma_{tt\gamma}}$ & $\boldsymbol{\sigma_{tt\gamma\gamma}}$ 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 $\rightarrow$ 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

- Inclusive cuts

- **NLO NNPDF3.1luxQED PDF** → 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 → Event is rejected unless below condition 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 → Collinear ($R \to 0$) radiation forbidden → Collinear splittings associated with fragmentation functions removed → Isolation applied in experimental analyses no longer reproduced

Smooth photon isolation prescription

$pp \to tt\gamma\gamma$

Stremmer, Worek, JHEP 08 (2023) 179

n = 1	$\sigma^{\mathrm{NLO}}_{\mathrm{Full}}$ [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

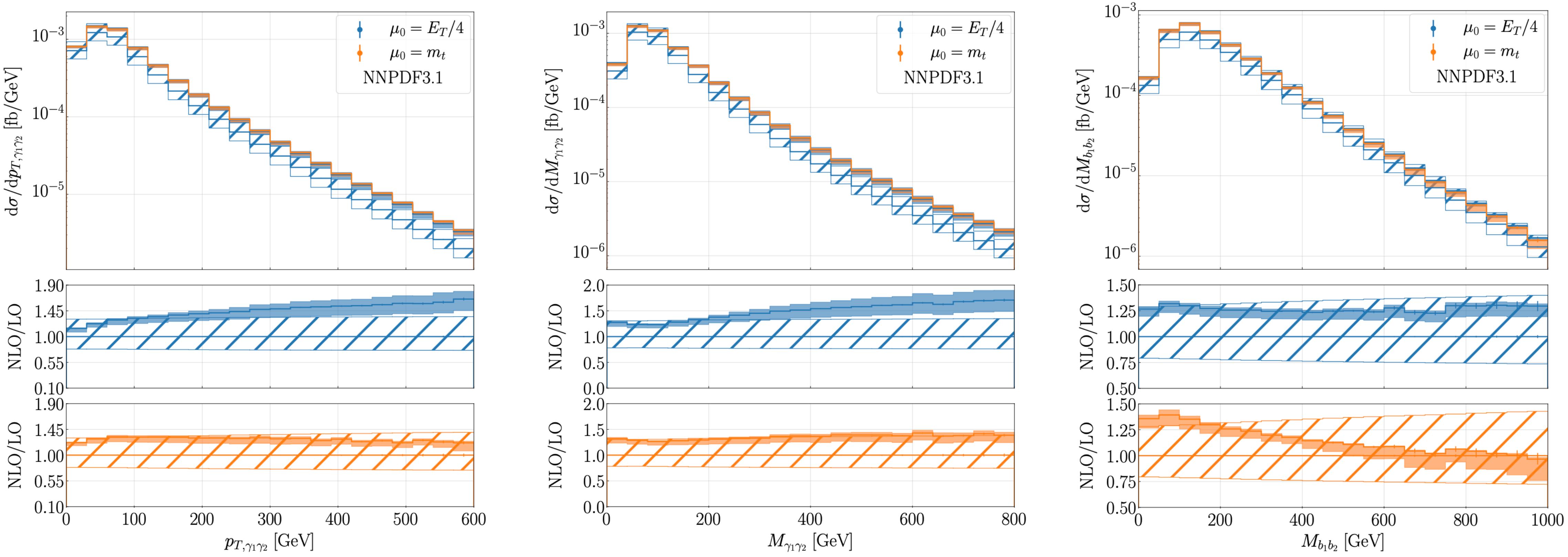
l+jets decay channel

In *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

$NLO_{QCD} = LO_1 + NLO_1$

$pp \to tt\gamma\gamma$



Stremmer, Worek, JHEP 08 (2023) 179

- Impact of NLO QCD effects on differential distributions substantial
- Size of higher-order corrections and uncertainties depends on observable & scale choice

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

$pp \to tt\gamma$

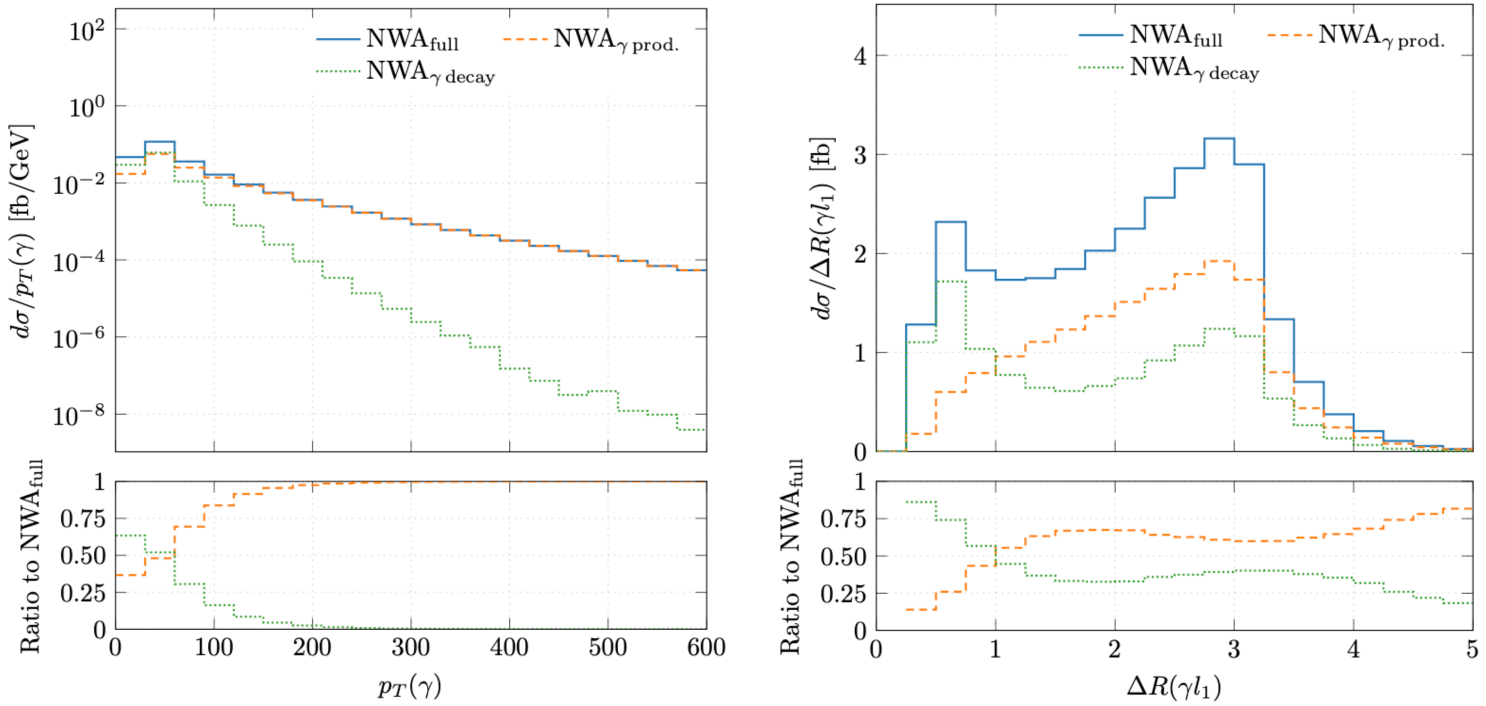
Production

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

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%*
- Differential level @ NLO QCD
  - Various phase-space regions with various effects



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

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

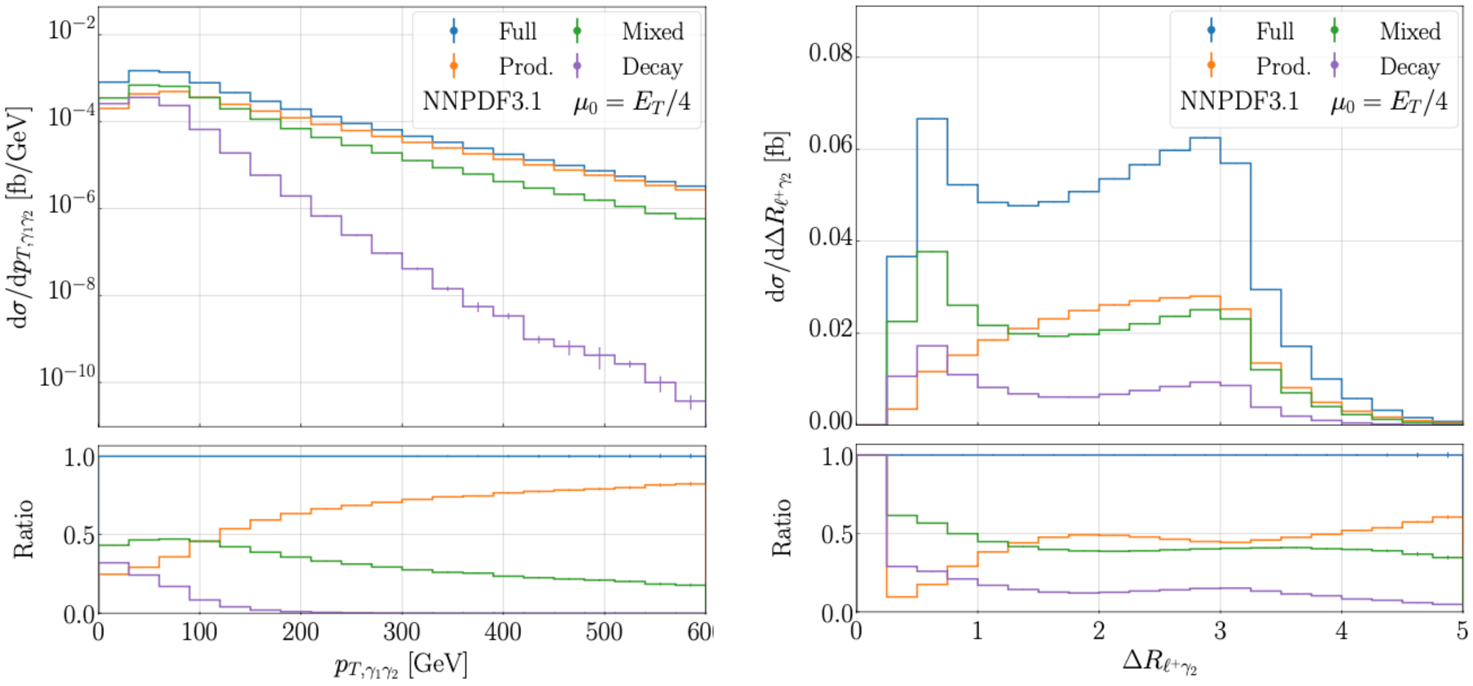
$pp \to tt\gamma\gamma$

- 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

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

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

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

$$\mathrm{LO} = \mathrm{LO_1} + \mathrm{LO_2} + \mathrm{LO_3}$$

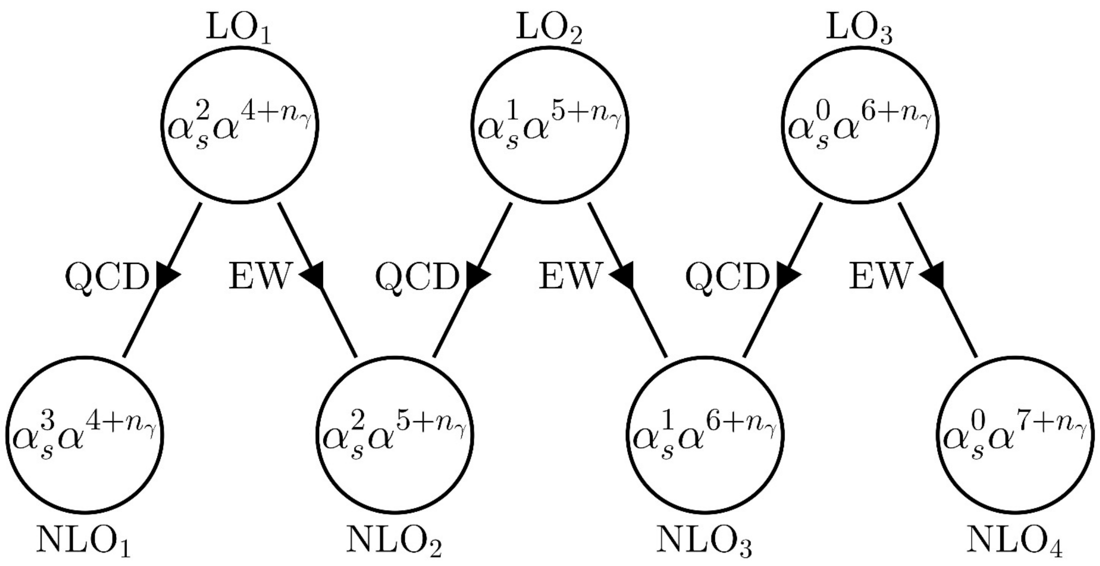
$$\mathrm{NLO_{QCD}} = \mathrm{LO_1} + \mathrm{NLO_1}$$

$$\mathrm{NLO} = \mathrm{LO_1} + \mathrm{LO_2} + \mathrm{LO_3} + \mathrm{NLO_1} + \mathrm{NLO_2} + \mathrm{NLO_3} + \mathrm{NLO_4}$$

$$\mathrm{NLO_{prd}} = \mathrm{LO_1} + \mathrm{LO_2} + \mathrm{LO_3} + \mathrm{NLO_1} + \mathrm{NLO_{2,prd}} + \mathrm{NLO_{3,prd}} + \mathrm{NLO_{4,prd}}$$

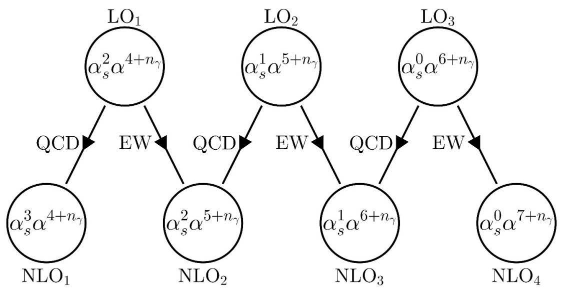
		σ_i [fb]	Ratio to $\mathrm{LO_1}$
$\mathrm{LO_1}$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$55.604(8)^{+31.4\%}_{-22.3\%}$	1.00
$\mathrm{LO_2}$	$\mathcal{O}(\alpha_s^1\alpha^6)$	$0.18775(5)^{+20.1\%}_{-15.4\%}$	+0.34%
$\mathrm{LO_3}$	$\mathcal{O}(\alpha_s^0\alpha^7)$	$0.26970(4)^{+14.3\%}_{-16.9\%}$	+0.49%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

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



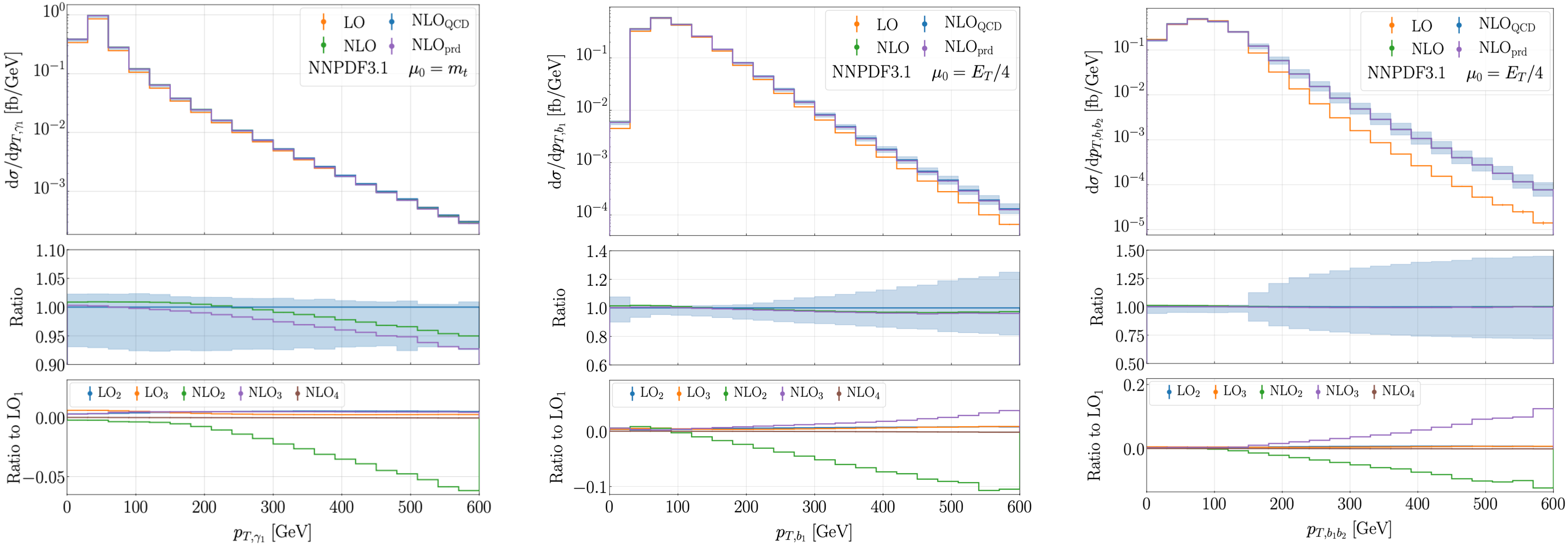
$\mathrm{NLO_{prd}}$ → photon bremsstrahlung & subleading NLO corrections in production only

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



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

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

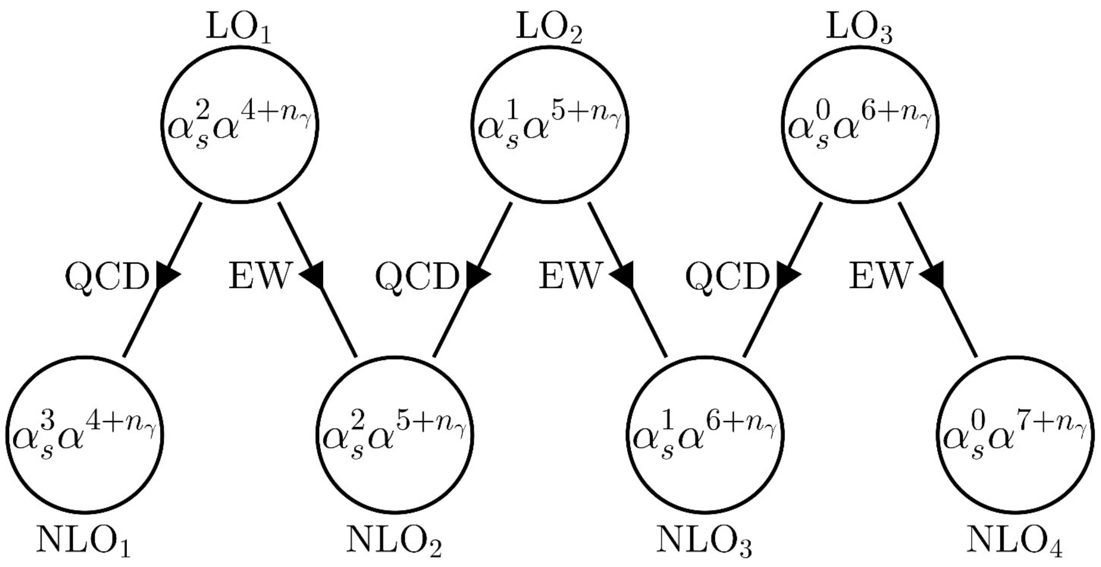


- EW Sudakov logarithms in NLO_2 leads to reduction in tails of up to *10%* compared to $\mathrm{NLO}_{\mathrm{QCD}}$ result
- Random cancellations between NLO_2 & NLO_3 → Should be considered together
- $\mathrm{NLO}_{\mathrm{prd}}$ approximation models complete NLO result very well

NLO_{QCD} & NLO_{PRD} & NLO

$pp \to tt\gamma\gamma$

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



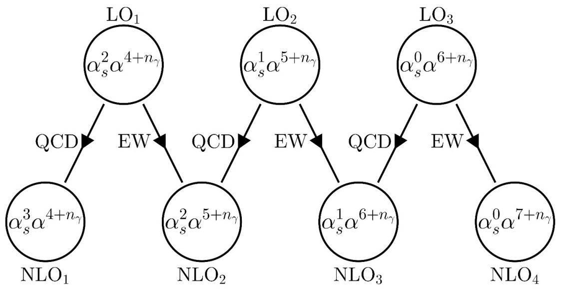
NLO_{prd} $\rightarrow$ photon bremsstrahlung & subleading NLO corrections in production only

- 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	$\mathcal{O}(\alpha_s^2\alpha^6)$	$0.15928(3)^{+31.3\%}_{-22.1\%}$	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
NLO_{QCD}		$0.1703(2)^{+1.9\%}_{-6.2\%}$	1.0690
NLO_{prd}		$0.1694(2)^{+1.7\%}_{-5.9\%}$	1.0637
NLO		$0.1700(2)^{+1.8\%}_{-6.0\%}$	1.0674

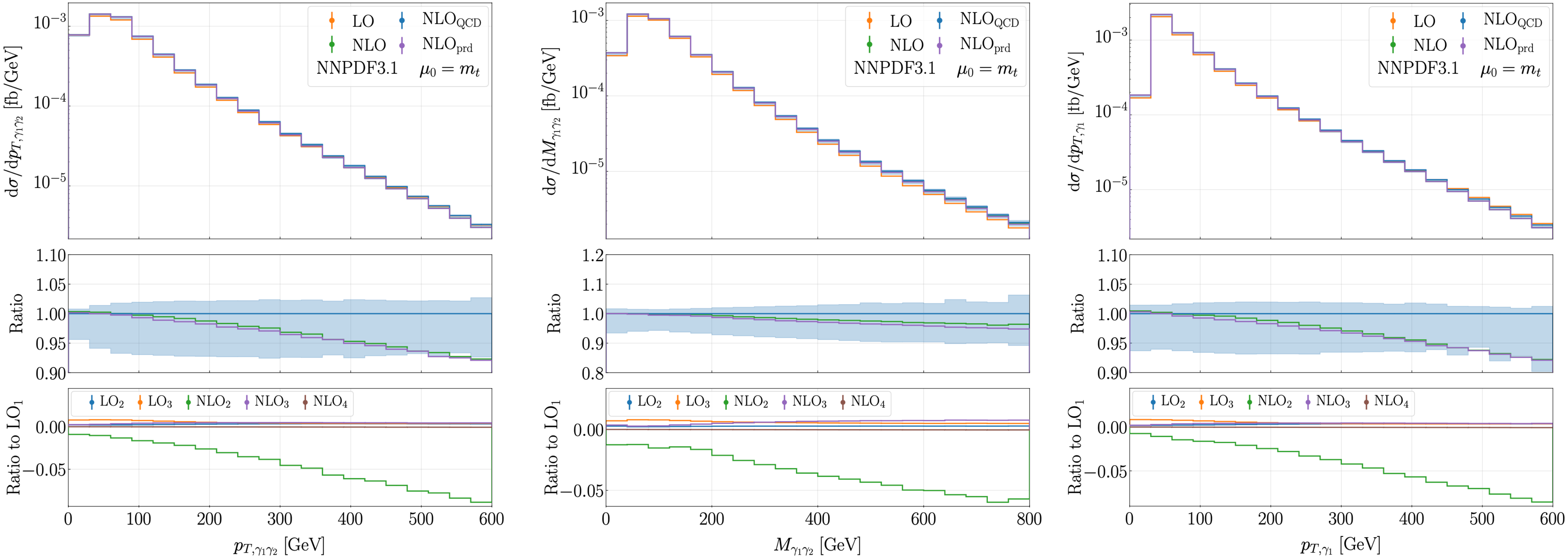
Stremmer, Worek e-Print: 2403.03796 [hep-ph]

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



$pp \to tt\gamma\gamma$

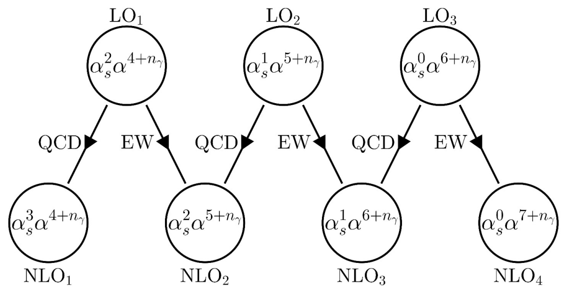
$pp \to ttH \to tt\gamma\gamma$



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

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

Summary



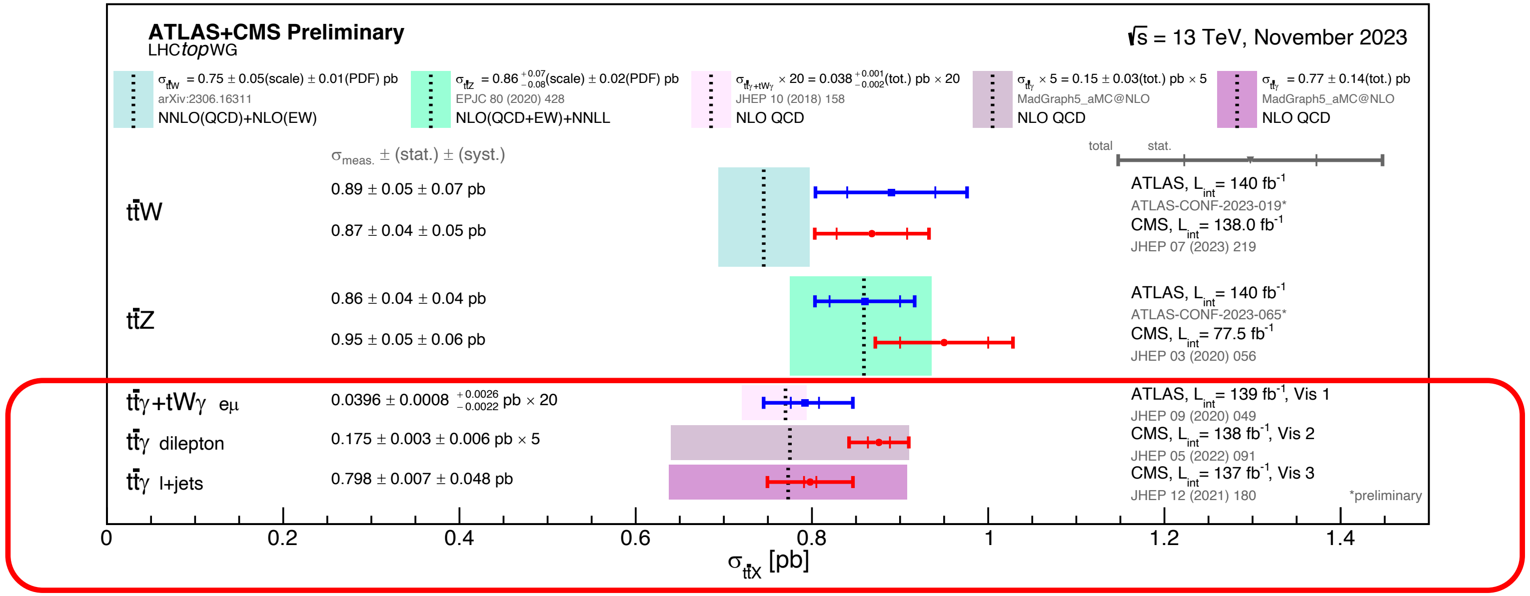
- Impact of NLO QCD effects on differential distributions substantial
- Size of higher-order corrections & uncertainties depends on observable & scale choice
- Overall → Higher order NLO QCD corrections important
- EW Sudakov logarithms in **NLO_2** leads to reduction in tails of up to *10%* compared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

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

Backup

Experimental Results

$pp \to tt\gamma$



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

CMS, JHEP 05 (2022) 091