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

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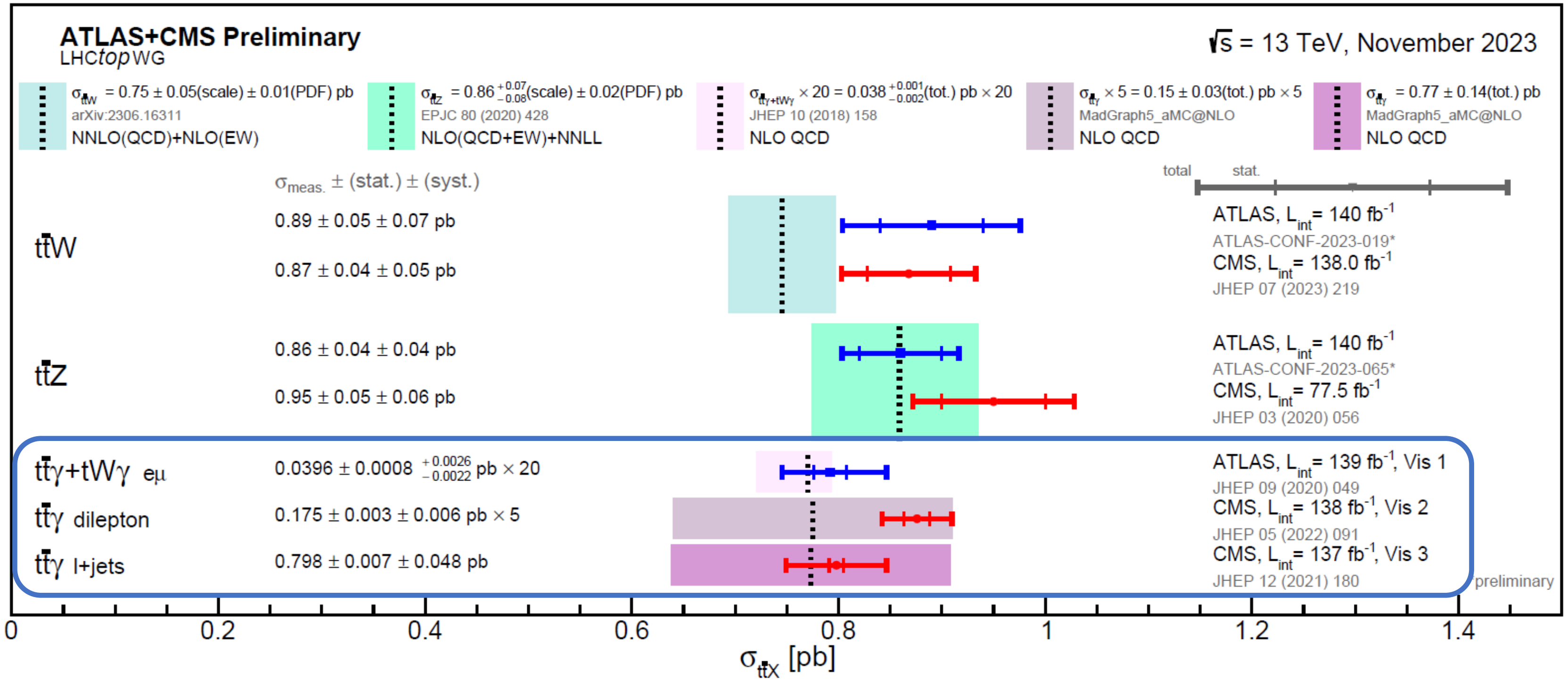
Collaborative Research Center TRR 257
P3H
Particle Physics Phenomenology after the Higgs Discovery

TOP2024, Saint-Malo, France, 23 September 2024

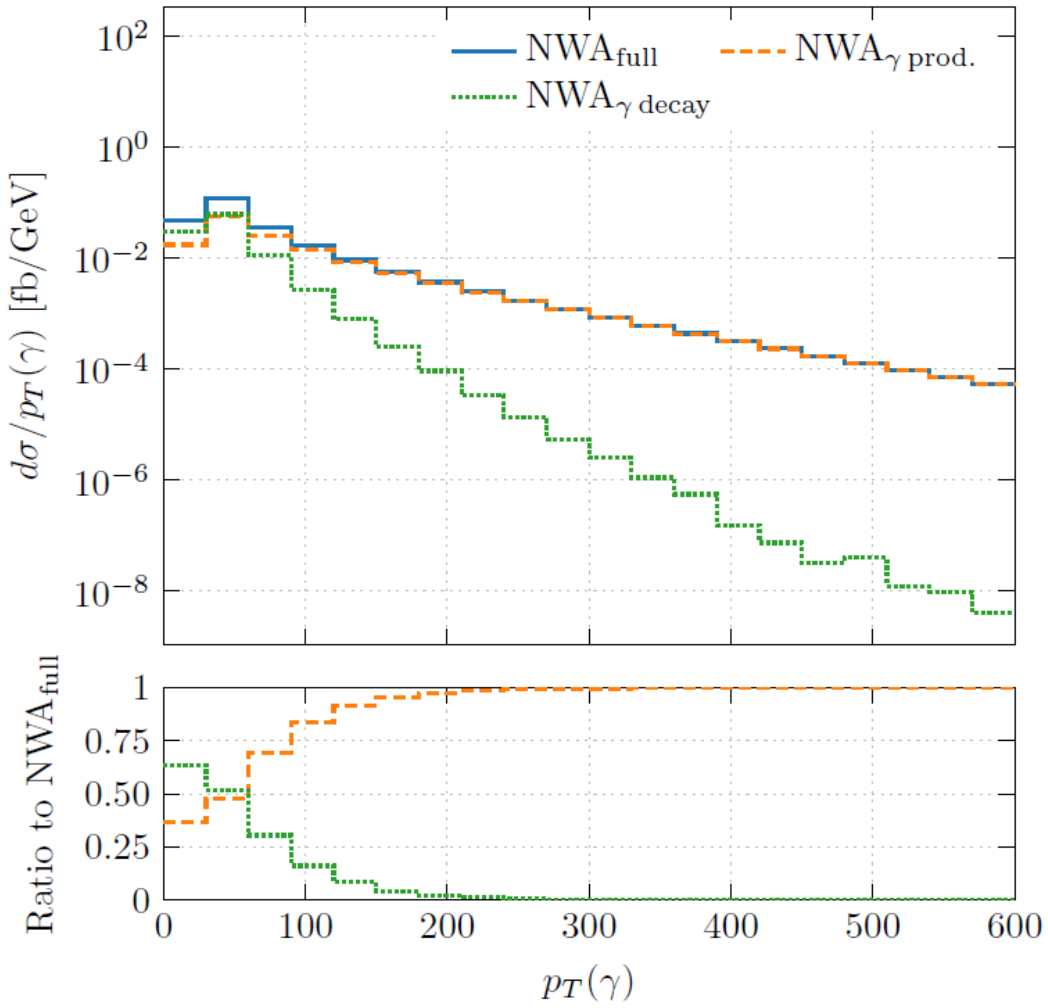
Motivation - pp → $t\bar{t}\gamma$

- Unique features with respect to other assoicated pp → $t\bar{t}$ processes:
  - Large fraction of photon radiation from top-quark decays ($t\bar{t}\gamma$: ~50%)
    → Difficult modeling
  - Secondary photon production due to fragmentation processes and hadron decays ($\pi^0 \rightarrow \gamma\gamma$)
    → Use of photon isolation criteria in measurements to suppress secondary photons
- Probe $t-\gamma$ coupling
- pp → $t\bar{t}\gamma$ first observed by ATLAS at 7 TeV *Phys.Rev.D 91 (2015) 7, 072007*

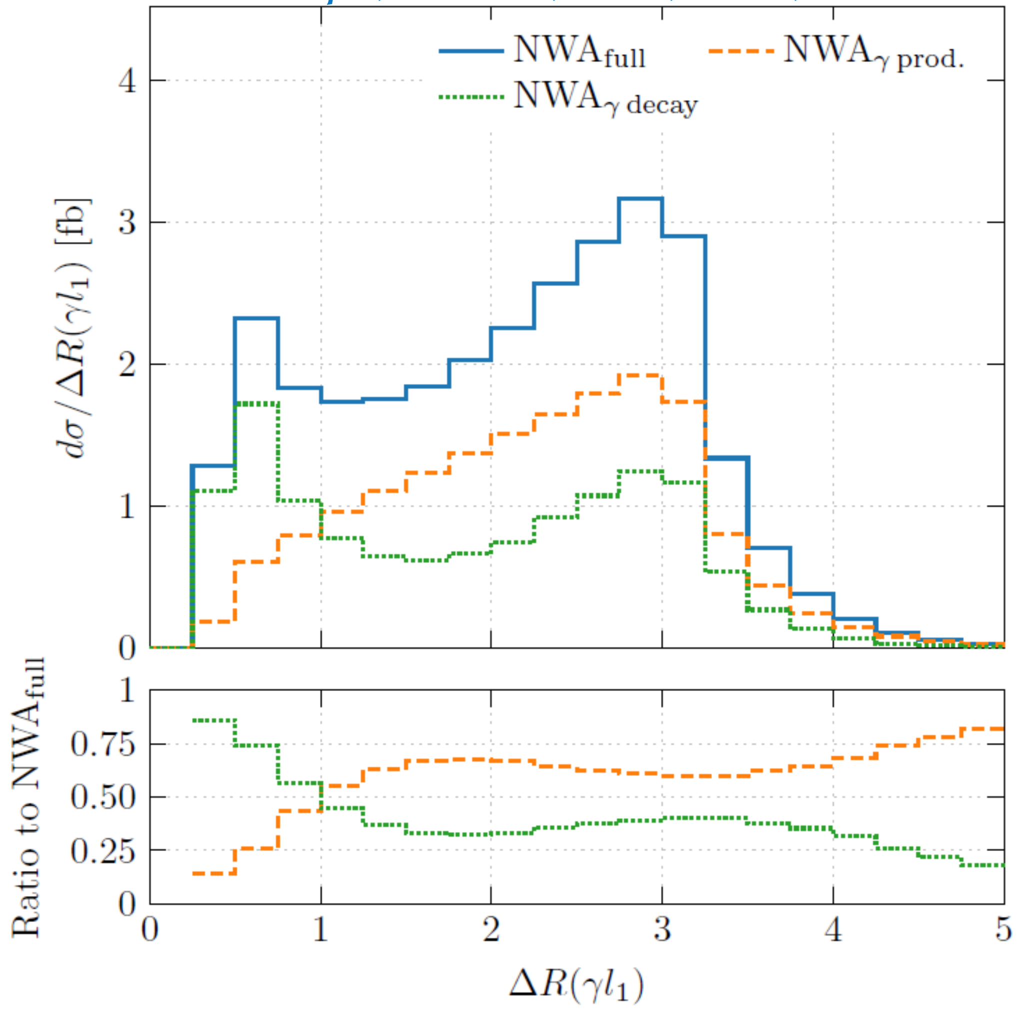
Current status:



Prompt photon distribution in pp → $t\bar{t}\gamma$ in di-lepton channel



Bevilacqua, Hartanto, Kraus, Weber, Worek '20

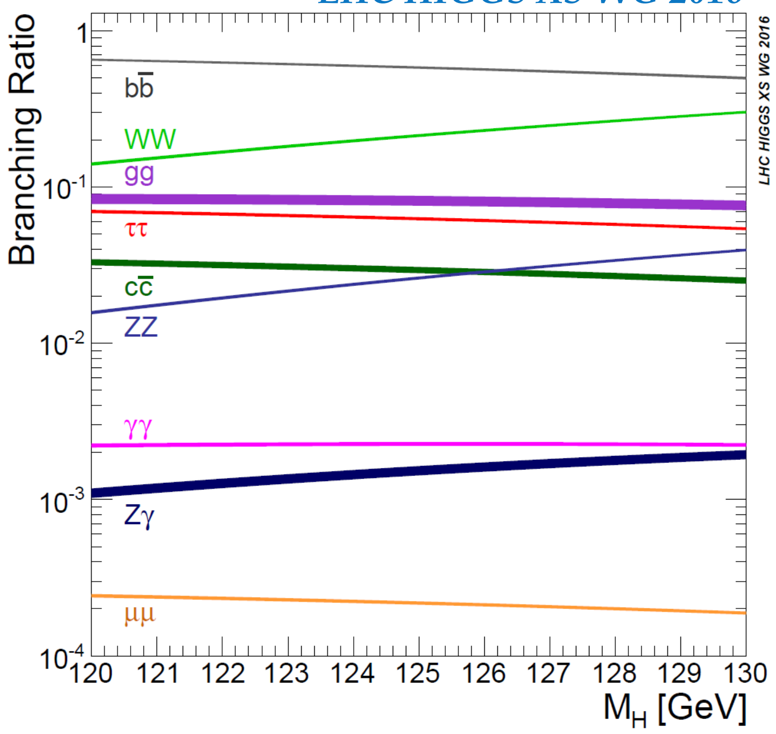


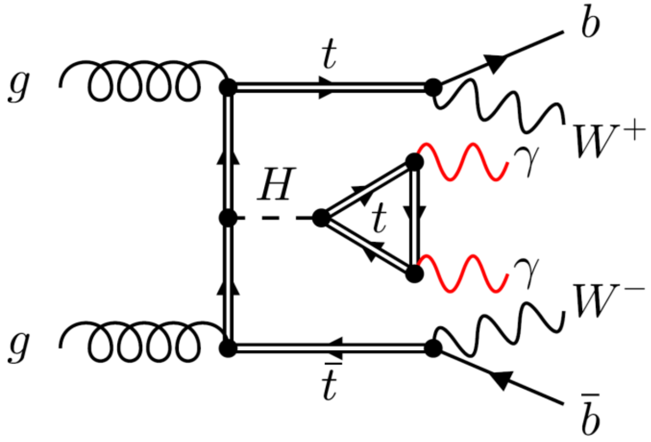
→ Essential to include photon radiation in top-quark decays

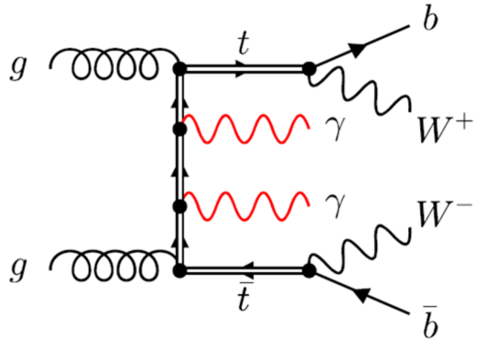
Motivation - pp → $t\bar{t}\gamma\gamma$

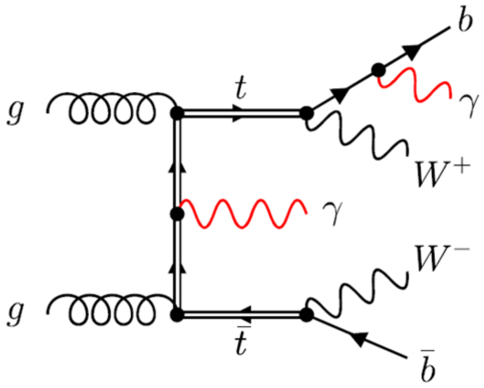
- Observation of pp → $t\bar{t}H$ in 2018 by ATLAS and CMS
  Phys.Lett.B 784 (2018) 173-191
  Phys.Rev.Lett. 120 (2018) 23, 231801
- Direct probe of Y_t at tree level
- H → γγ small branching ratio with ~0.2%
- pp → $t\bar{t}H$(H → γγ) first single-channel observation of pp → $t\bar{t}H$
  Phys.Rev.Lett. 125 (2020) 6, 061801
  Phys.Rev.Lett. 125 (2020) 6, 061802
- Irreducible background from direct photon production pp → $t\bar{t}\gamma\gamma$
- No observation of pp → $t\bar{t}\gamma\gamma$ yet

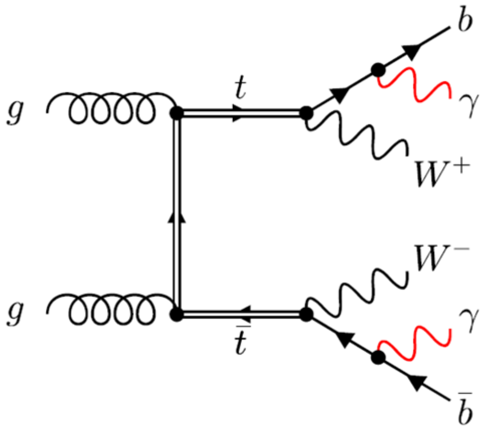
LHC HIGGS XS WG 2016











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

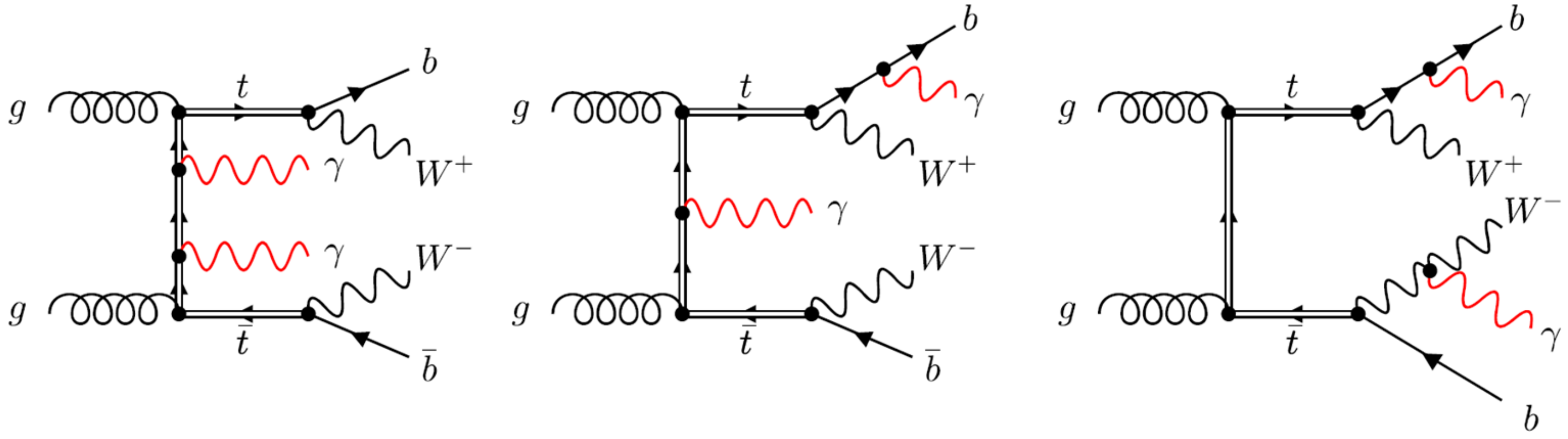
- Stable top quarks
  - NLO QCD — *Duan, Ma, Zhang, Han, Guo, Wang '09 '11; Maltoni, Pagani, Tsinikos '16*
  - NLO EW — *Duan, Zhang, Wang, Song, Li '17*
  - Complete NLO — *Pagani, Shao, Tsinikos, Zaro '21*
  - aNNLO QCD — *Kidonakis, Tonero,'21*
- Matched to Parton showers at NLO QCD
  - POWHEL/POWHEG — *Kardos, Trócsányi '15*
- Higher order corrections and photon radiation in decays
  - NLO QCD in NWA — *Melnikov, Schulze, Scharf '11; Bevilacqua, Hartanto, Kraus, Weber, Worek '20*
  - NLO QCD with full off-shell effects — *Bevilacqua, Hartanto, Kraus, Weber, Worek '18*
  - Complete NLO in NWA — *Stremmer, Worek '24*
- All calculations based on smooth-cone isolation *Frixione '98*

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

- Stable top quarks at NLO QCD
  - NLO QCD — *Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro '14*; *Maltoni, Pagani, Tsinikos '16*
  - 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*
- Higher order corrections and photon radiation in decays
  - NLO QCD in NWA — *Stremmer, Worek '23*
  - Complete NLO in NWA — *Stremmer, Worek '24*
- All calculations based on smooth-cone isolation *Frixione '98*

Process definition

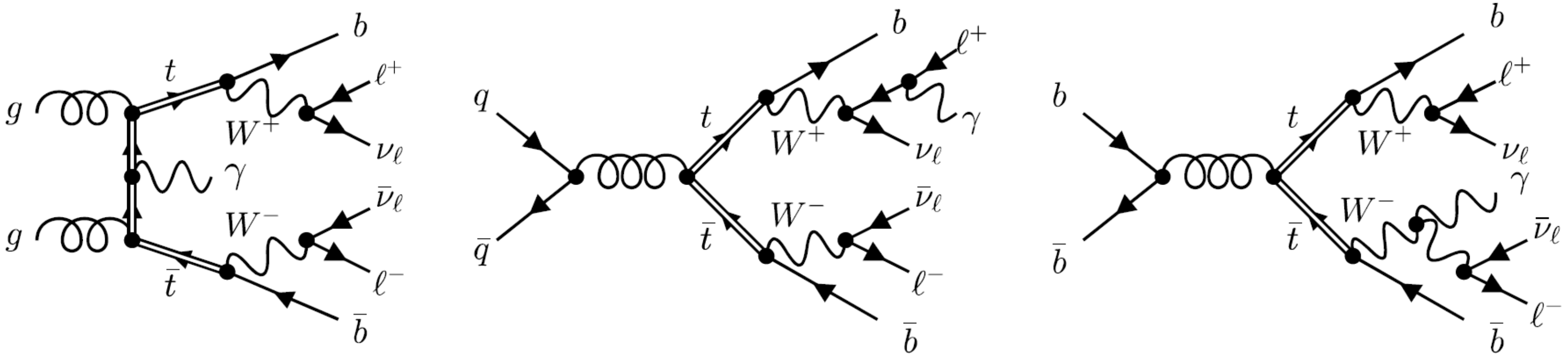
$$d\sigma^{\rm LO}_{\rm Full} = \Gamma_t^{-2}\big(\underbrace{d\sigma^{\rm LO}_{t\bar{t}\gamma\gamma}\, d\Gamma^{\rm LO}_{t\bar{t}}}_{\rm Prod.} + \underbrace{d\sigma^{\rm LO}_{t\bar{t}\gamma}\, d\Gamma^{\rm LO}_{t\bar{t}\gamma}}_{\rm Mixed} + \underbrace{d\sigma^{\rm LO}_{t\bar{t}}\, d\Gamma^{\rm LO}_{t\bar{t}\gamma\gamma}}_{\rm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



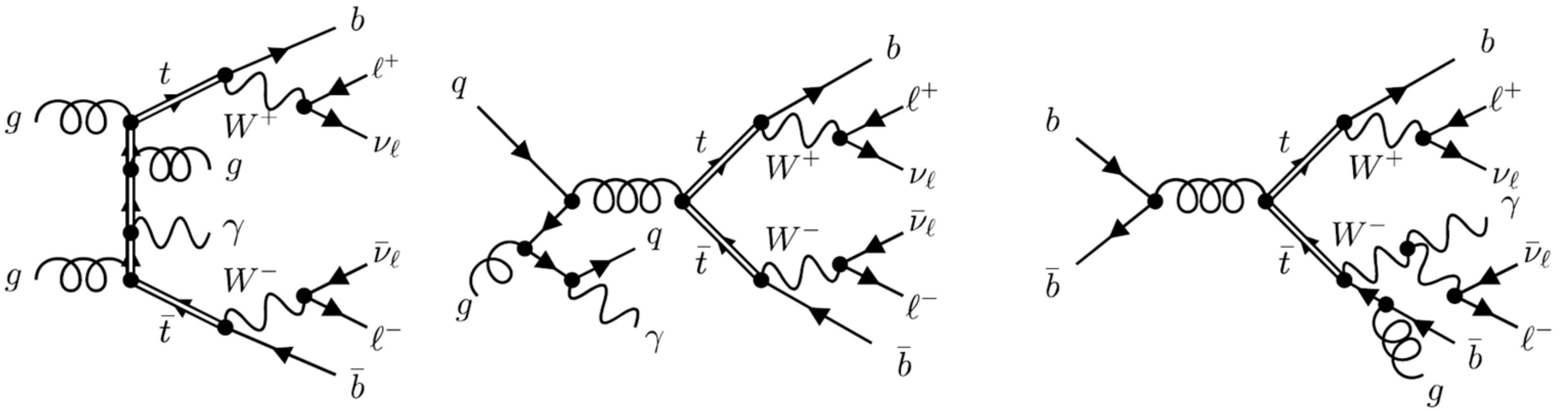
- Calculation performed in NWA preserving spin correlations
- Full calculation divided into three resonant contributions: Prod., Mixed and Decay
- Photon bremsstrahlung and NLO corrections included in $t\bar{t}$ production and decays
- NLO QCD corrections calculated for each resonant structure separately
- Mixing of resonant contributions in subleading NLO corrections

NLO QCD

LO_1 at $\mathcal{O}(\alpha_s^2 \alpha^{4+n_\gamma})$

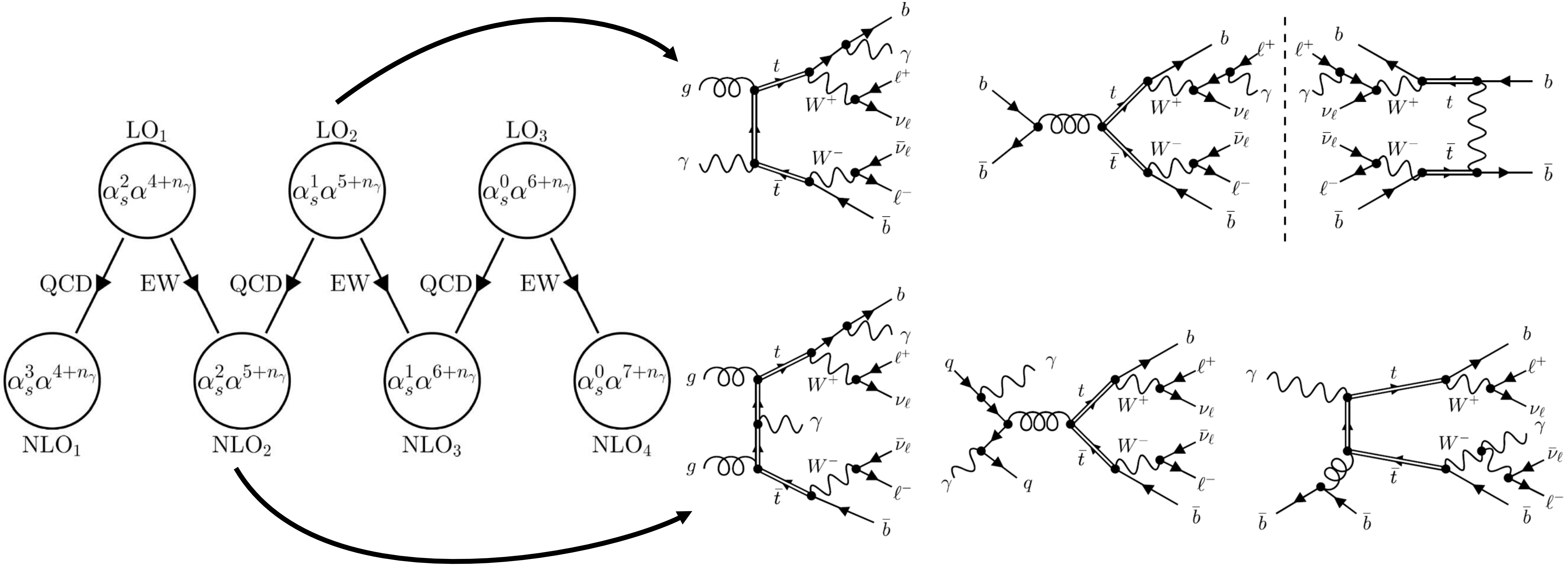


NLO_1 at $\mathcal{O}(\alpha_s^3 \alpha^{4+n_\gamma})$



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

Complete NLO



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

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

Computational framework

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

- Further Modifications in Recola
  - Random polarisation method $\sum_{\lambda} |\mathcal{M}_\lambda|^2 = \frac{1}{2\pi} \int_0^{2\pi} d\phi \, |\mathcal{M}_\phi|^2$
  - Alternative reduction to scalar integrals with CutTools *(Ossola, Papadopoulos, Pittau '09)* and OneLOop *(van Hameren '11)*
  - Mixed renormalisation of α : $\alpha^n = \alpha_{G_\mu}^{n-n_\gamma} \alpha(0)^{n_\gamma}$

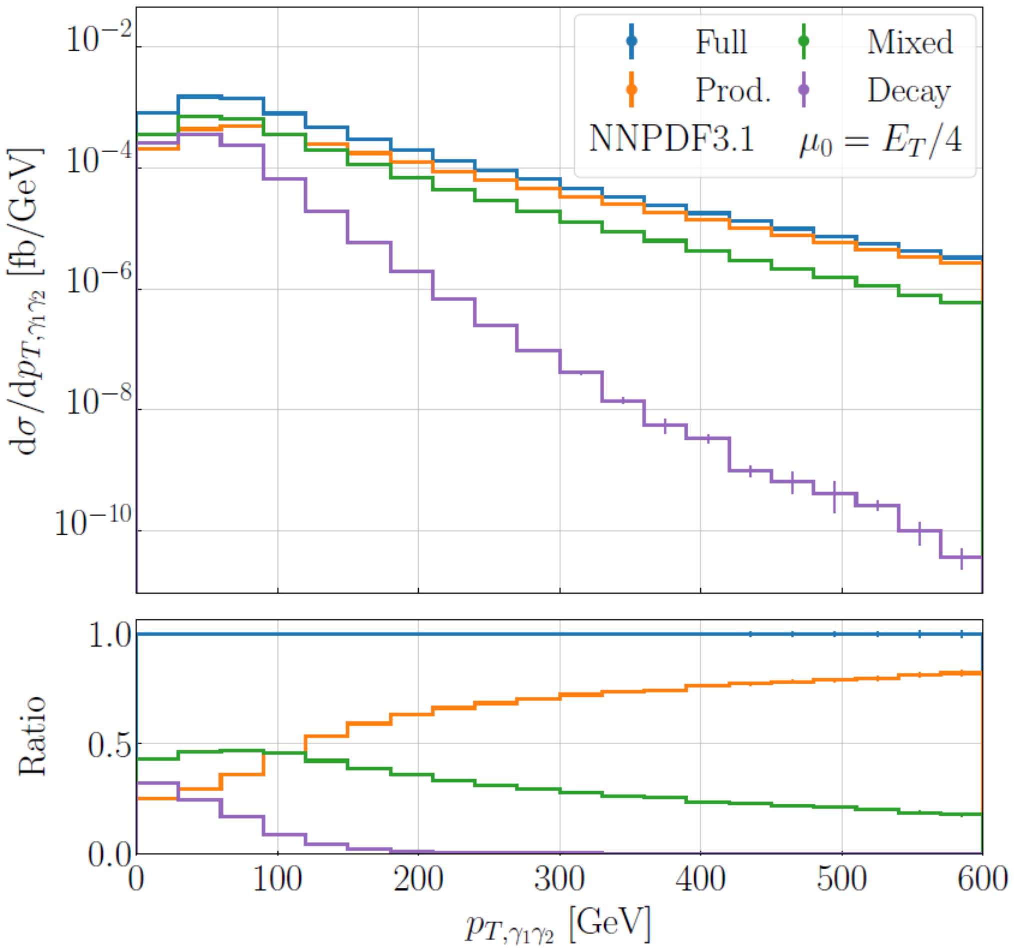
Real Corrections in Helac-Dipoles

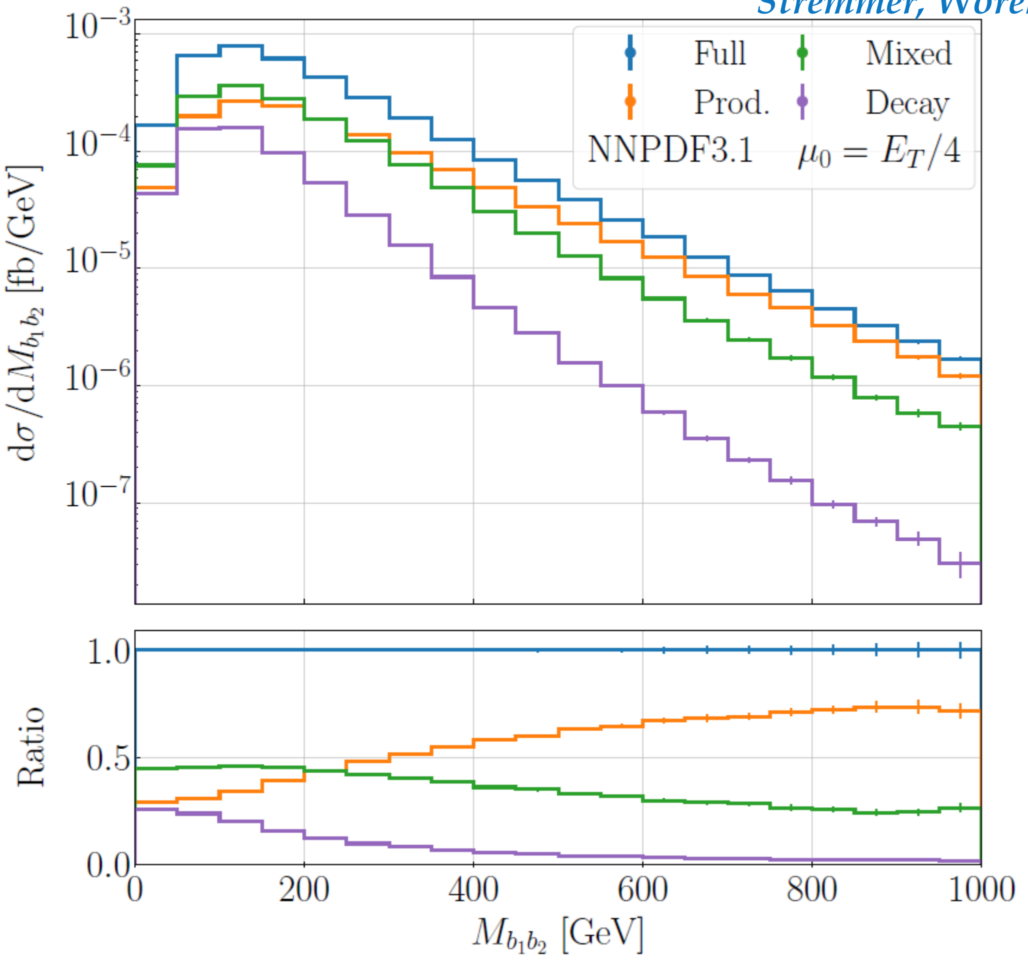
- Nagy-Soper subtraction *Bevilacqua, Czakon, Kubocz, Worek '13*
  - Extended to QCD and QED-like subtraction in nested decay chains with massive/massless emitters
- Partially cross-checked with Catani-Seymour subtraction *Catani, Seymour '97* *Catani, Dittmaier, Seymour, Trocsanyi '02*

- 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, PDF sets and observables

Prompt photon distribution in pp → $t\bar{t}\gamma\gamma$ in di-lepton channel at NLO QCD

Stremmer, Worek '23

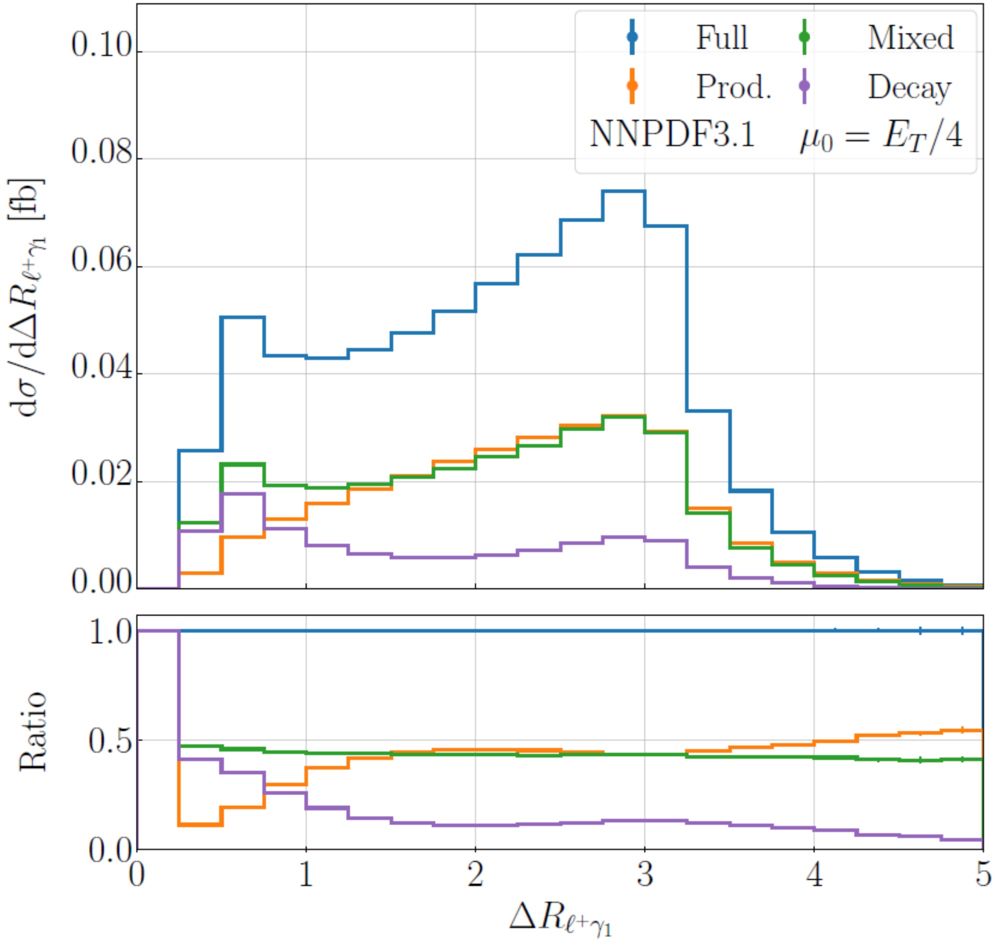


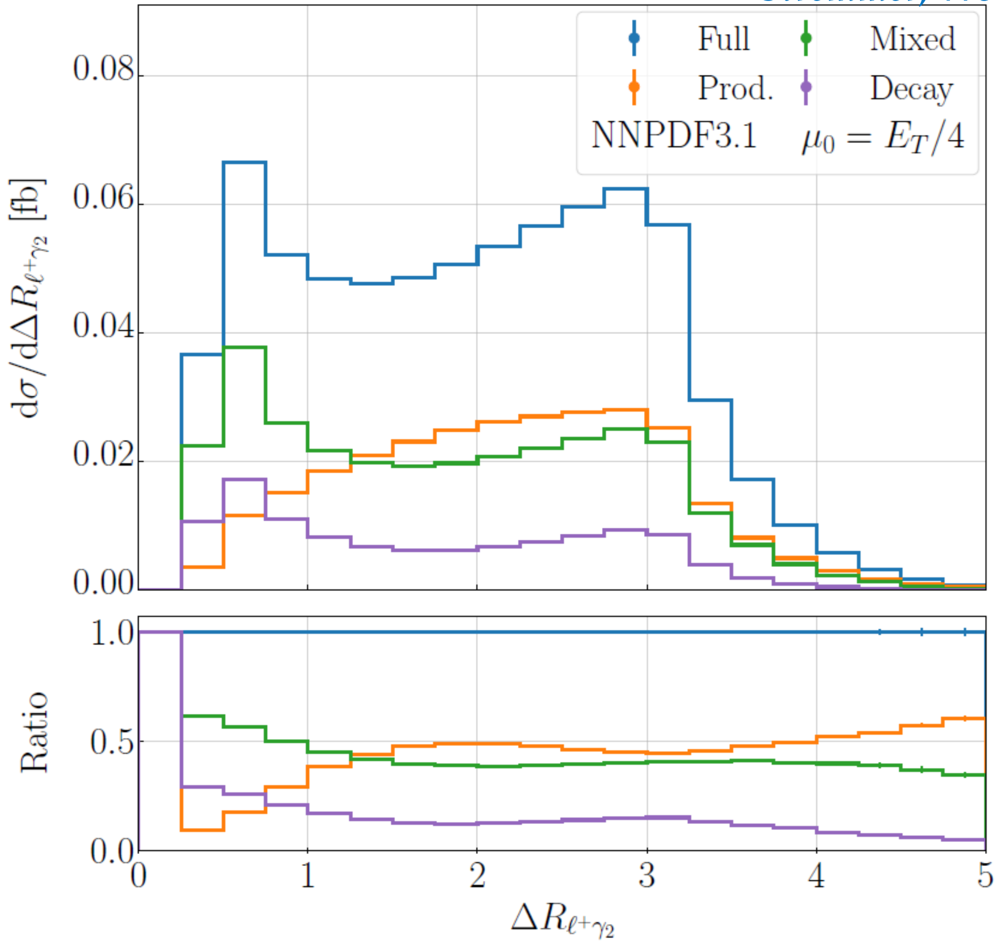


- Integrated level: Full = Prod. (40%) + Mixed (44%) + Decay (16%)
- Large contributions from photon emission in decays in bulk of distribution
- Tails dominated by Prod. (79 – 82% of Full)

Prompt photon distribution in pp → $t\bar{t}\gamma\gamma$ in di-lepton channel at NLO QCD

Stremmer, Worek '23



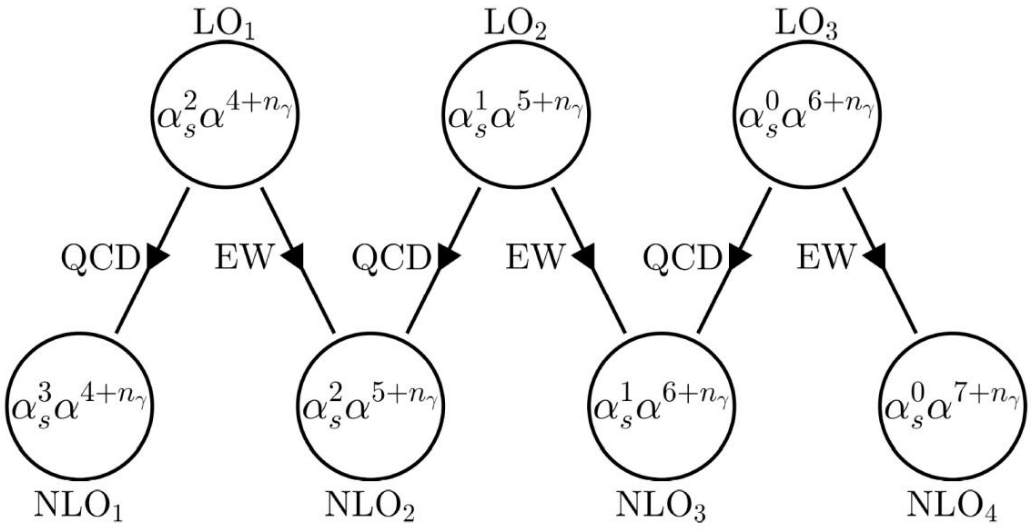


- Different peak structures for Prod., Mixed and Decay
- Only sum leads to reliable predictions
- Similar conclusions in lepton + jet top-quark decay channel

Complete NLO predictions for pp → $t\bar{t}\gamma$ in di-lepton channel

		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
$\mathrm{NLO}_{\mathrm{QCD}}$		$59.05(5)^{+1.6\%}_{-5.9\%}$	1.0620
$\mathrm{NLO}_{\mathrm{prd}}$		$59.08(5)^{+1.5\%}_{-5.9\%}$	1.0626
NLO		$59.59(5)^{+1.6\%}_{-5.9\%}$	1.0717

Stremmer, Worek '24

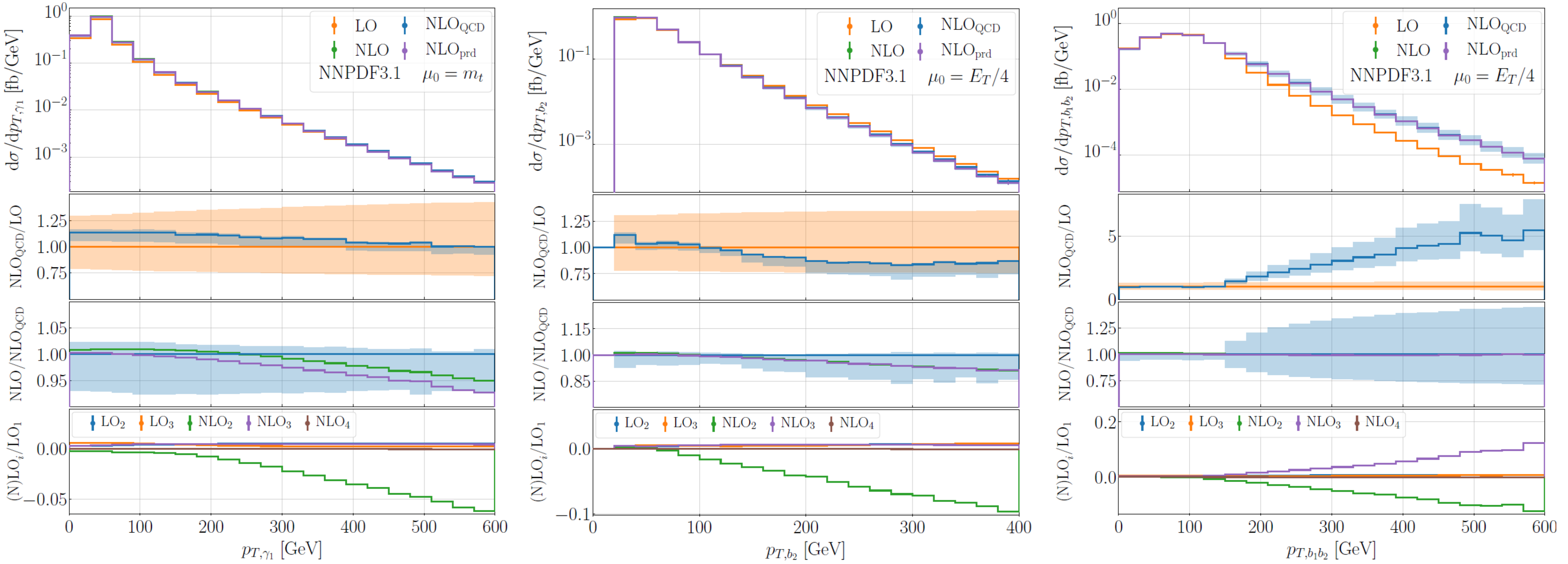


- Subleading LO contributions below 1%
- NLO corrections dominated by NLO_1
- Subleading NLO corrections below 1%
- Similar conclusions for pp → $t\bar{t}\gamma\gamma$

- $\mathrm{NLO}_{\mathrm{prd}} = \mathrm{LO}_1 + \mathrm{LO}_2 + \mathrm{LO}_3 + \mathrm{NLO}_1 + \mathrm{NLO}_{2,\mathrm{prd}} + \mathrm{NLO}_{3,\mathrm{prd}} + \mathrm{NLO}_{4,\mathrm{prd}}$
- No photon radiation and higher-order corrections in top-quark decays in subleading NLO contributions

Complete NLO predictions for pp → $t\bar{t}\gamma$ in di-lepton channel

Stremmer, Worek '24



- Subleading NLO corrections as large as 10% due to EW Sudakov logarithms in NLO$_2$
- Accidental cancellations between NLO$_2$ and NLO$_3$ → Should be considered together
- Negligible differences between NLO$_{prd}$ and NLO of less than 2%

Photon isolation criteria

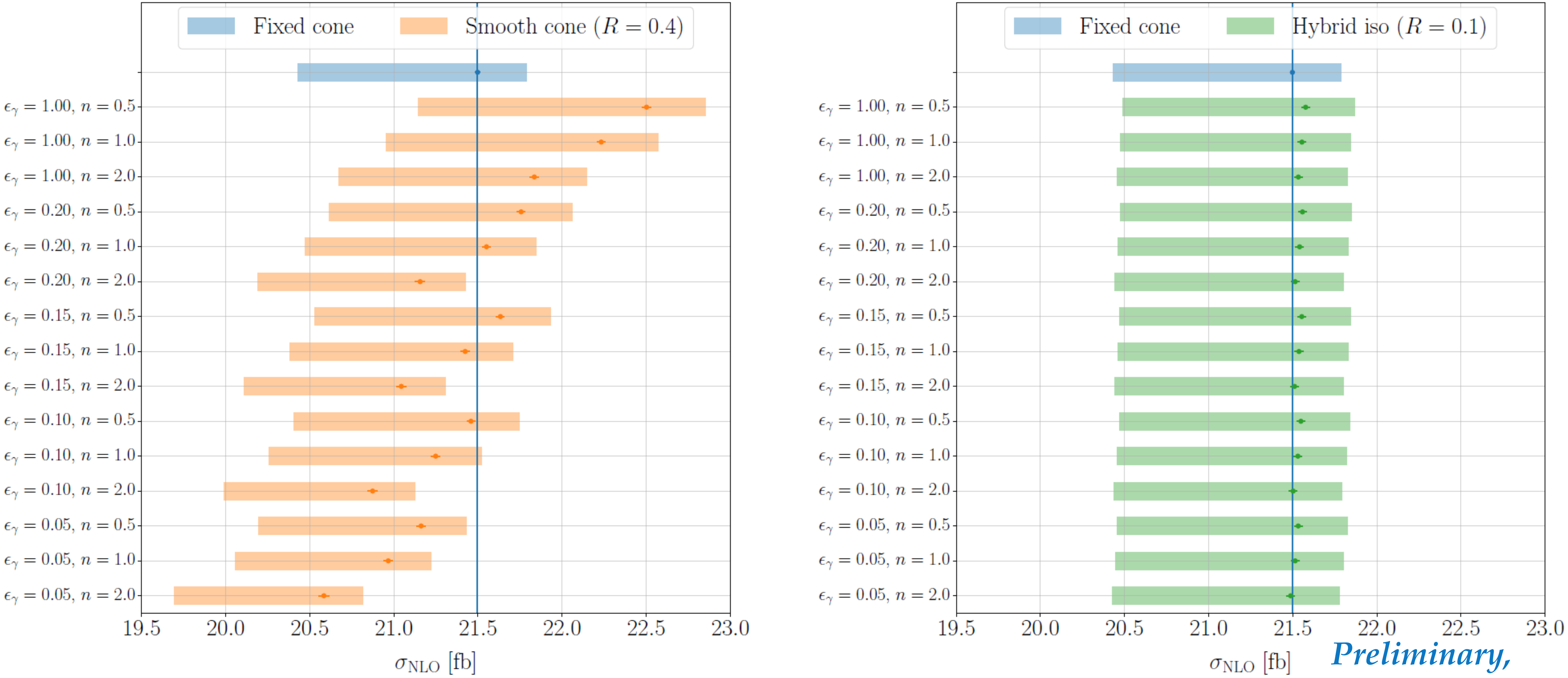
- Smooth-cone isolation *Frixione '98*
  - $E_{T,\mathrm{had}}(R) \leq \epsilon_\gamma \, E_{T,\gamma} \left(\frac{1-\cos(R)}{1-\cos(R_{\gamma j})} \right)^n \quad \text{for all } R \leq R_{\gamma j}$
  - Removes collinear photon-quark configurations → Removes fragmentation contribution
  - Cannot directly be used in experiments
  - Input parameters ϵ_γ, n (and $R_{\gamma j}$) are arbitrary

- Fixed-cone isolation
  - $E_{T,\mathrm{had}}(R_{\gamma j}) \leq E_{T,\max}(E_{T,\gamma})$
  - Collinear photon-quark configurations allowed
  - $\mathrm{d}\hat{\sigma}^{\gamma+X,\mathrm{NLO}} = \mathrm{d}\hat{\sigma}_\gamma^{\mathrm{NLO}} + \sum_p \mathrm{d}\hat{\sigma}_p^{\mathrm{LO}} \otimes D_{p\to\gamma} - \frac{\alpha}{2\pi} \sum_p \mathrm{d}\hat{\sigma}_p^{\mathrm{LO}} \otimes \mathbf{\Gamma}_{p\to\gamma}^{(0)}$

- Hybrid photon isolation
  - First use smooth-cone isolation to remove fragmentation contribution and then the fixed-cone isolation
  - Reduces dependence on (arbitrary) input parameters in smooth-cone isolation

- Setup based on recent ATLAS analysis: *arXiv: 2403.09452 [hep-ex]*
  - $E_{T,\mathrm{had}}(R=0.4) < 0.022 \cdot E_{T,\gamma} + 2.45 \text{ GeV}$ and $E_{T,\mathrm{had}}(R=0.2) < 0.05 \cdot E_{T,\gamma}$
  - ALEPH LO quark-to-photon fragmentation function

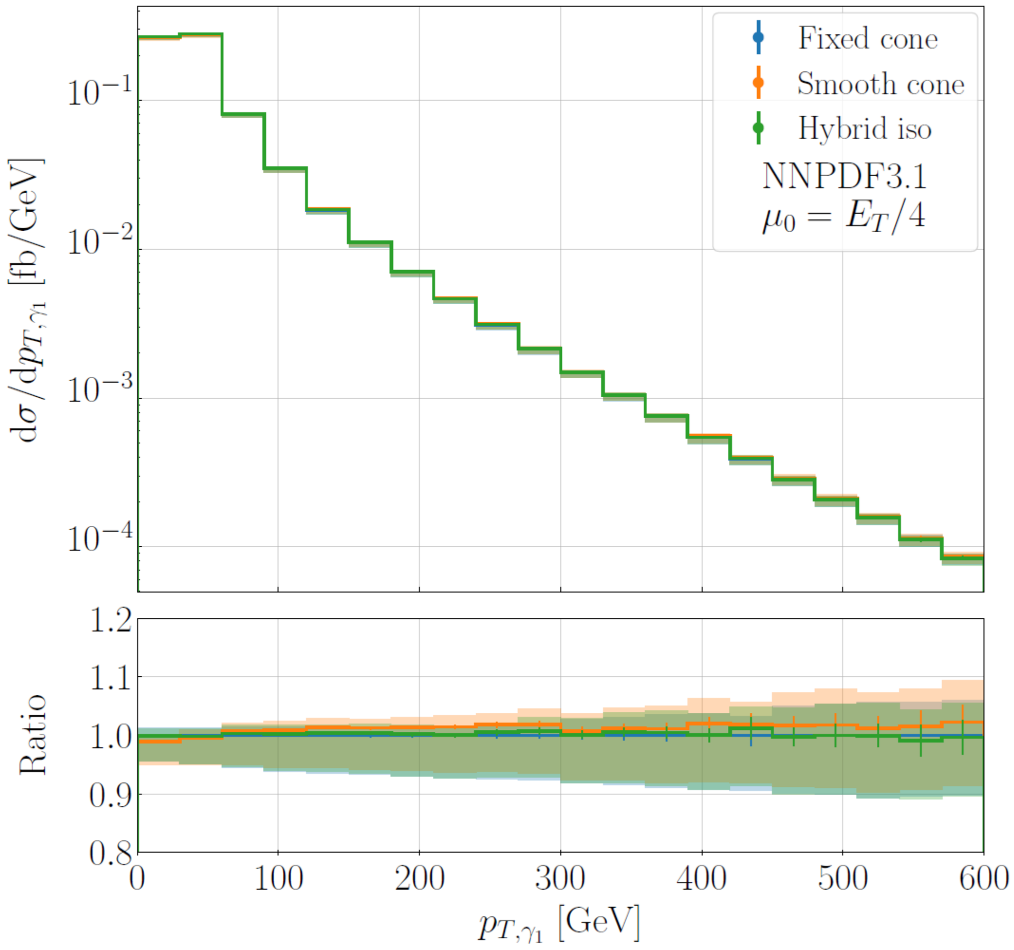
Photon isolation in pp → $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ at $\sqrt{s} = 13.6$ TeV

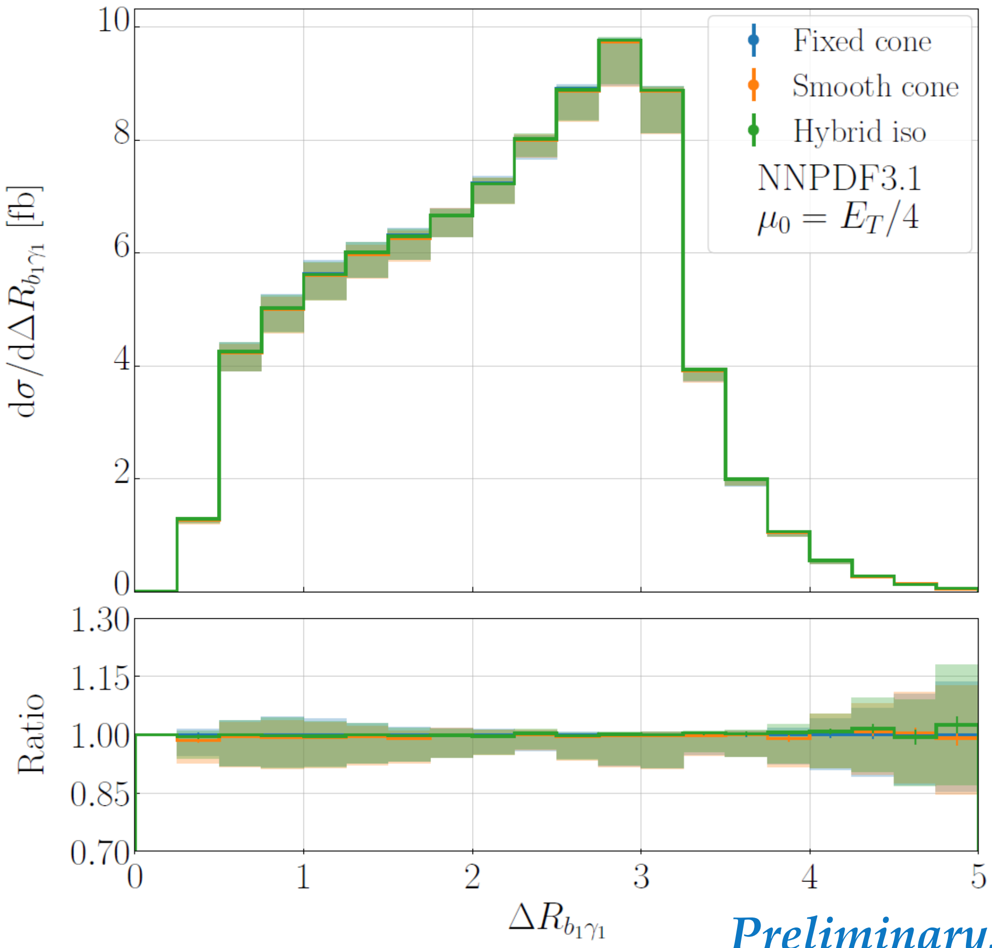


Preliminary, Stremmer, Worek

- Fragmentation contribution negligible small with ~0.2%
- Differences up to 5% between fixed-cone and smooth-cone isolation → Similar to scale uncertainties
- Hybrid photon isolation reduces dependence on input parameters in (inner) smooth-cone isolation

Photon isolation in pp $\rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ at $\sqrt{s} = 13.6$ TeV

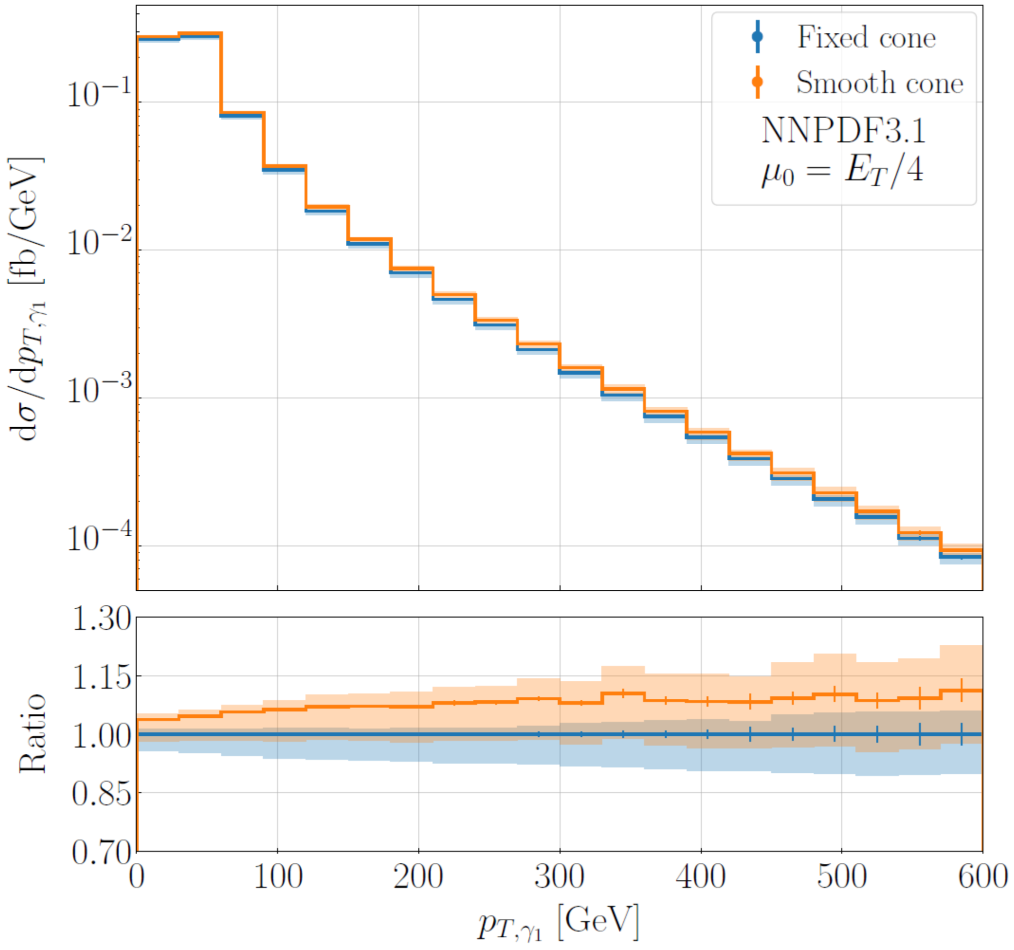


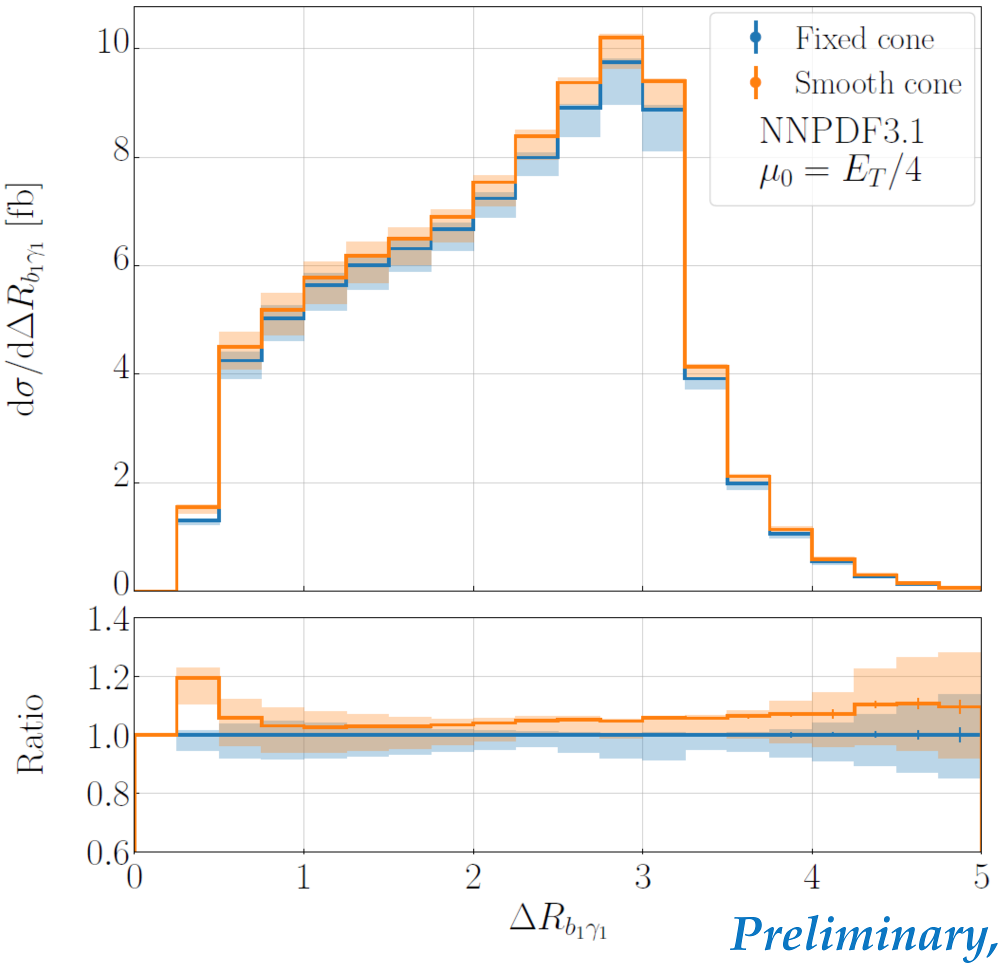


Preliminary, Stremmer, Worek

- Smooth cone isolation: $(R = 0.4, \epsilon_\gamma = 0.10, n = 0.5)$
- Hybrid photon isolation: $(R = 0.1, \epsilon_\gamma = 0.10, n = 2.0)$
- Negligible differences for tuned smooth-cone and hybrid photon isolation conditions

Photon isolation in $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ at $\sqrt{s} = 13.6$ TeV





Preliminary, Stremmer, Worek

- Smooth cone isolation: $(R = 0.4, \epsilon_\gamma = 1.00, n = 0.5)$
- Significant and non-constant differences without tuning of parameters

Conclusion

- Prompt photon distribution in $pp \to t\bar{t}\gamma\gamma$ in the NWA
  - Only 40% of integrated fiducial cross section from Prod.
  - Only sum of all resonant contributions leads to accurate predictions

- Calculation of complete NLO corrections in $pp \to t\bar{t}\gamma$ and $pp \to t\bar{t}\gamma\gamma$ in the NWA
  - Enhancement of EW Sudakov logarithms in NLO_2 → Reduction in tails up to 10%
  - Accidental cancellations between NLO_2 and NLO_3 → Should be considered together
  - $\mathrm{NLO}_{\mathrm{prd}}$ is good approximation → Sufficient to include subleading NLO corrections in $t\bar{t}\gamma(\gamma)$ producion

- First calculation of $pp \to t\bar{t}\gamma$ at NLO QCD with fixed-cone isolation
  - Small fragmentation contribution ~0.2%
  - Large dependence on input parameters in smooth-cone isolation → Requires tuning of parameters
  - Basically no dependence on input parameters in hybrid photon isolation

Outlook

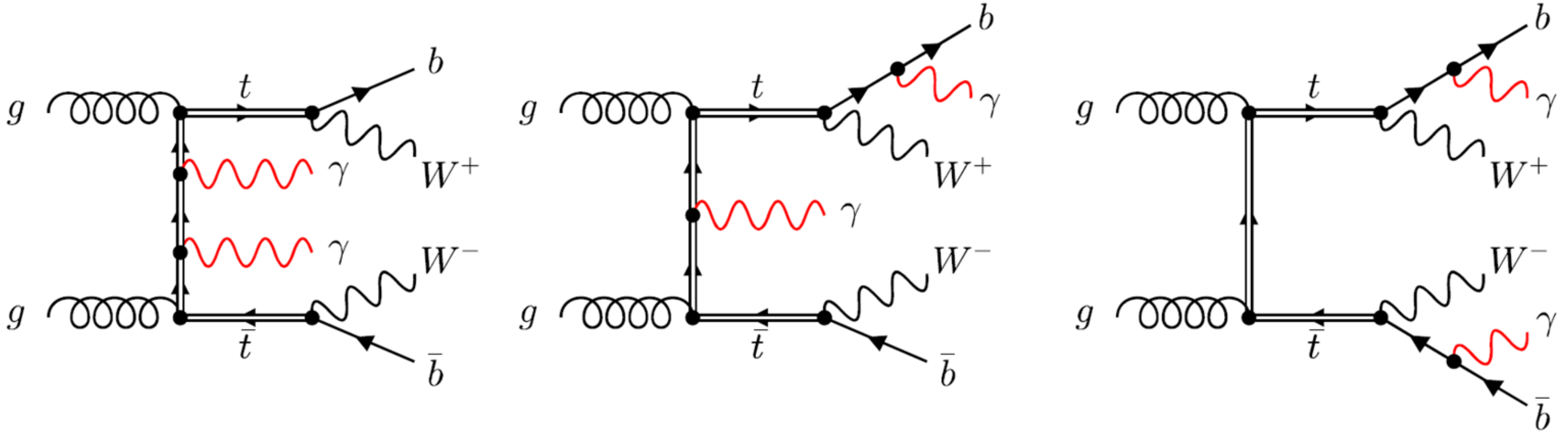
- Extend study of realistic photon isolation condition to $pp \to t\bar{t}\gamma\gamma$ and lepton + jet top-quark decay channel
- Comparisons with experimental measurements

Backup

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 ($\Gamma_t^{NLO}(\mu_R = m_t)$)



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(luxQED) NLO PDF set with $\alpha_s(M_Z) = 0.118$

- Smooth-cone isolation *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*

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:

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

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

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

- Modifications in fixed-cone isolation setup:
- $n_b \geq 2$, $\quad p_{T,\gamma} > 20 \text{ GeV}\,, \quad |y_\gamma| < 2.37$

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

Stremmer, Worek '23

- 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

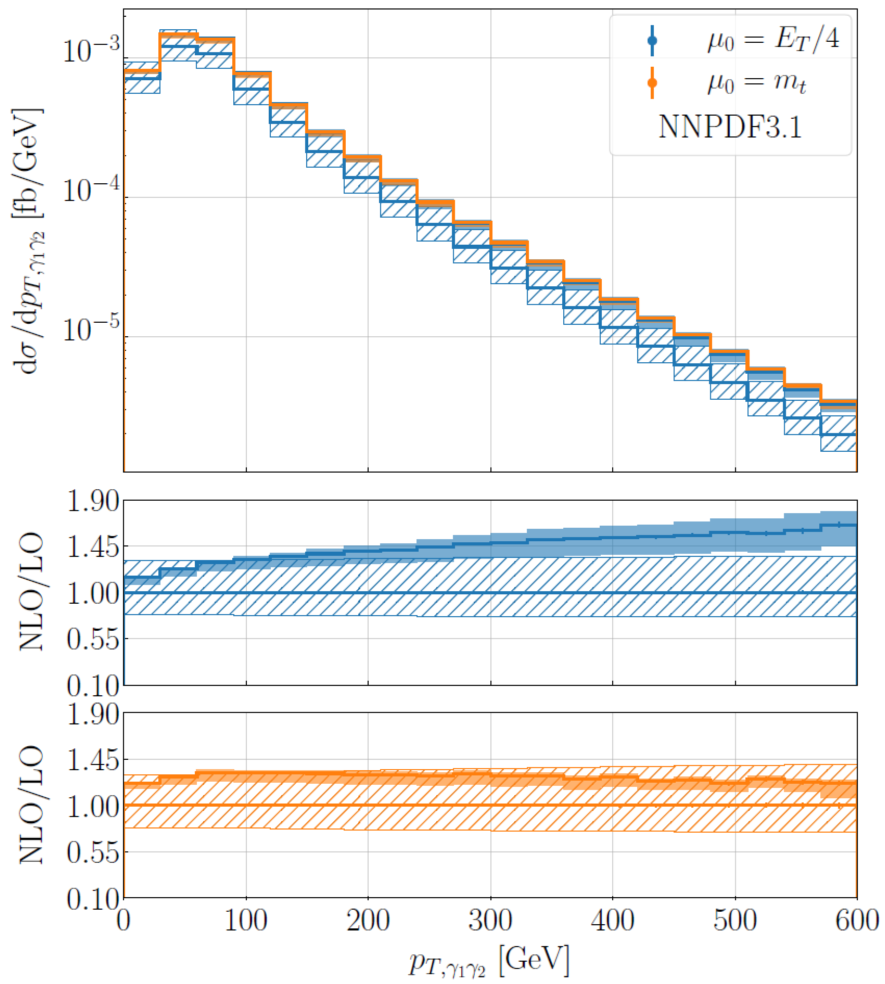
		gg	gg/pp	$q\bar{q}$	$q\bar{q}/pp$	$qg + \bar{q}g$	$(qg + \bar{q}g)/pp$
$\sigma^{\mathrm{NLO}}_{\mathrm{Full}}$	[fb]	0.0999(1)	56.4%	0.04307(4)	24.3%	0.03428(4)	19.3%
$\sigma^{\mathrm{NLO}}_{\mathrm{Prod.}}$	[fb]	0.02587(4)	36.3%	0.02672(4)	37.5%	0.01871(3)	26.2%
$\sigma^{\mathrm{NLO}}_{\mathrm{Mixed}}$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

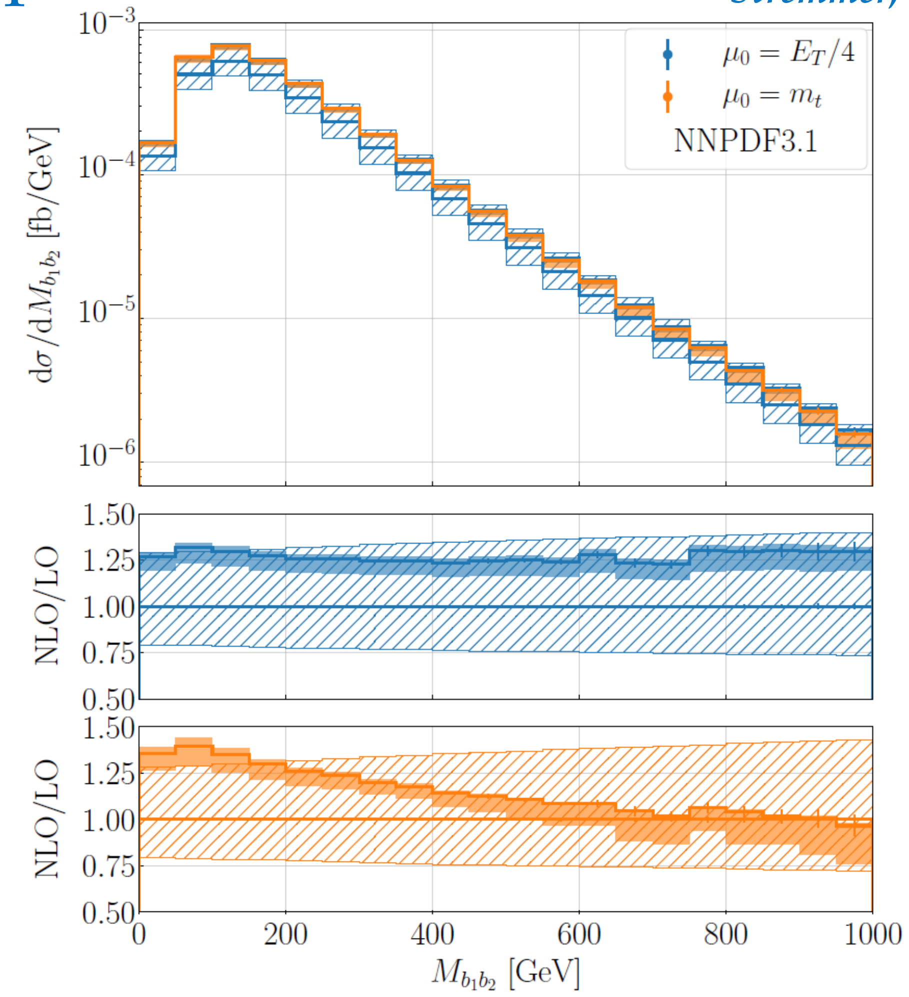
Stremmer, Worek ‘23

- 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 in di-lepton channel

Stremmer, Worek '23



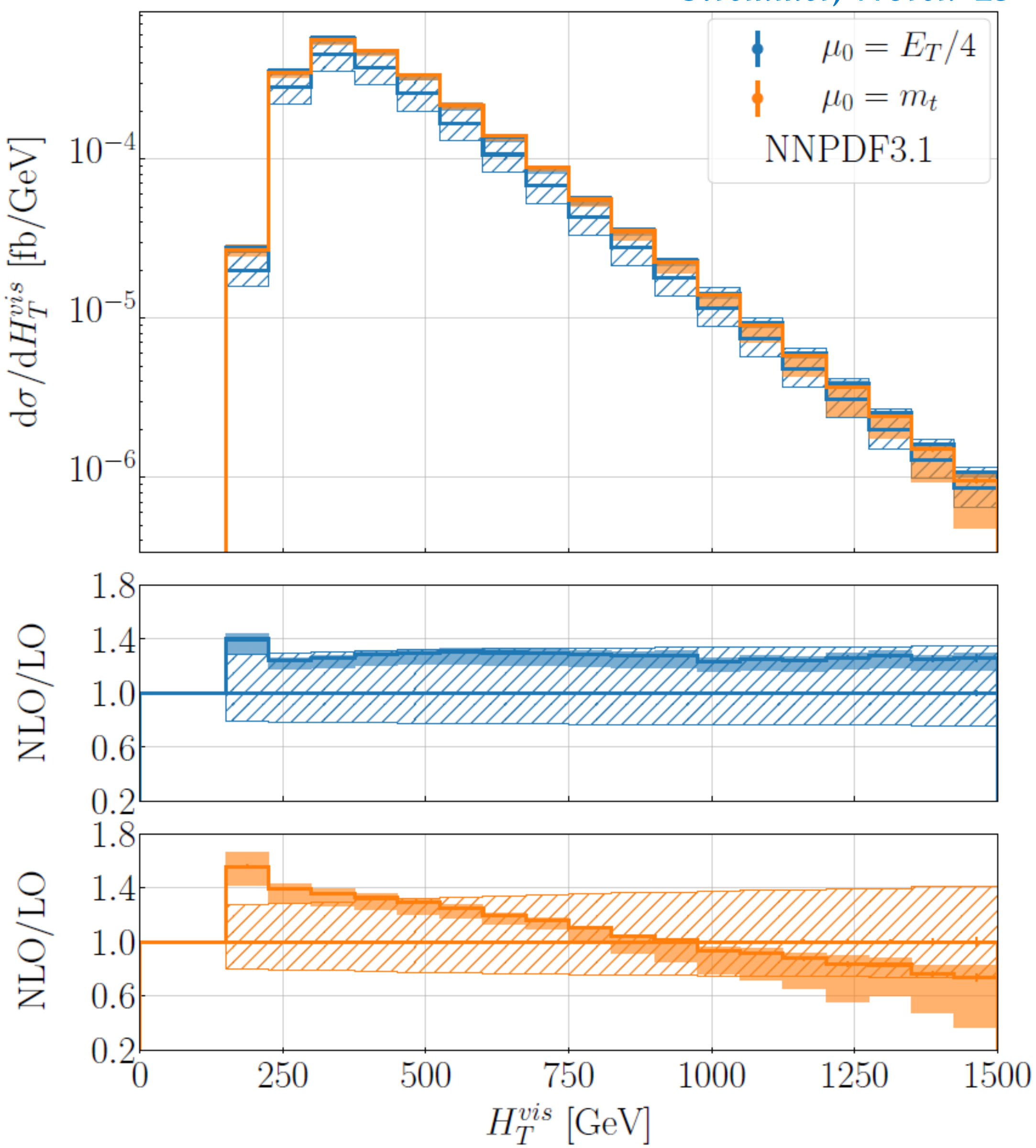


- NLO QCD corrections up to 65%
- Smaller corrections for $\mu_0 = m_t$
- Scale uncertainties 5% – 13%

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

Differential Fiducial cross section in di-lepton channel

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

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%

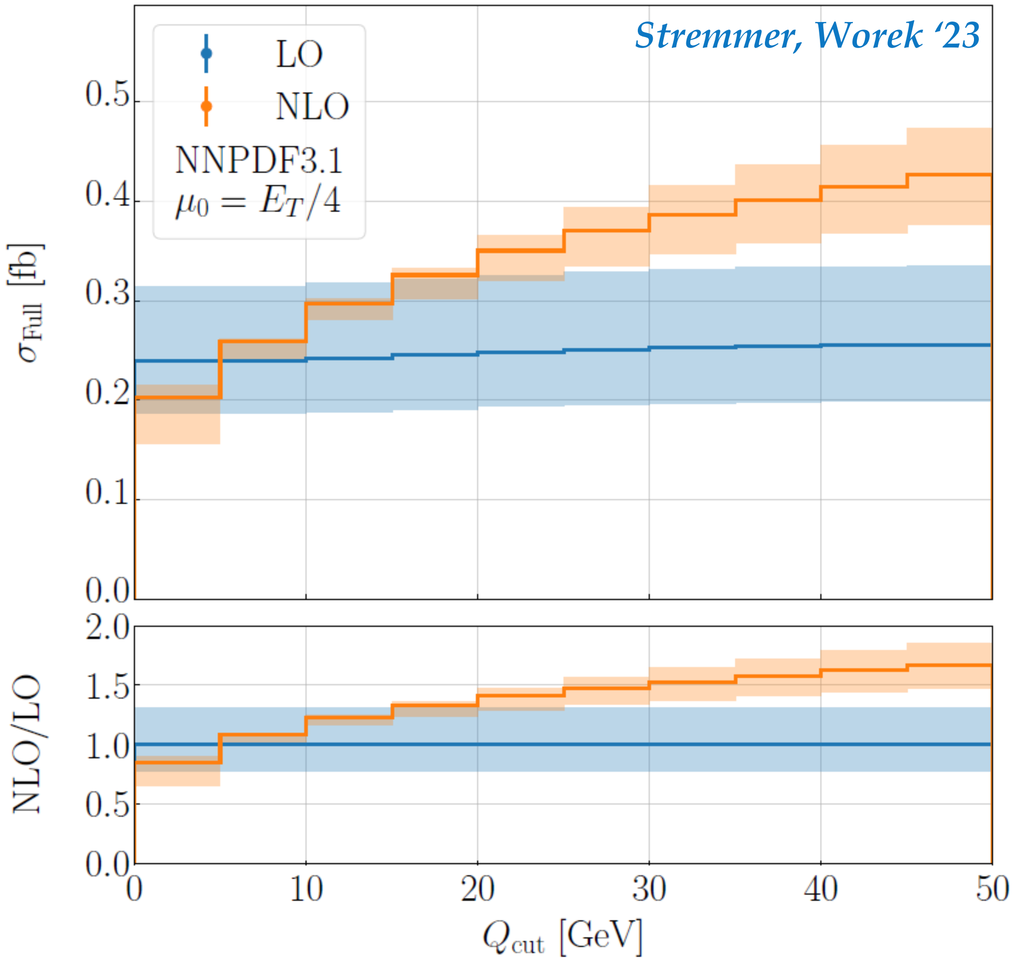
- Prod. increased from 40% (di-lepton) to 48% (lepton + jet) because of by additional cut

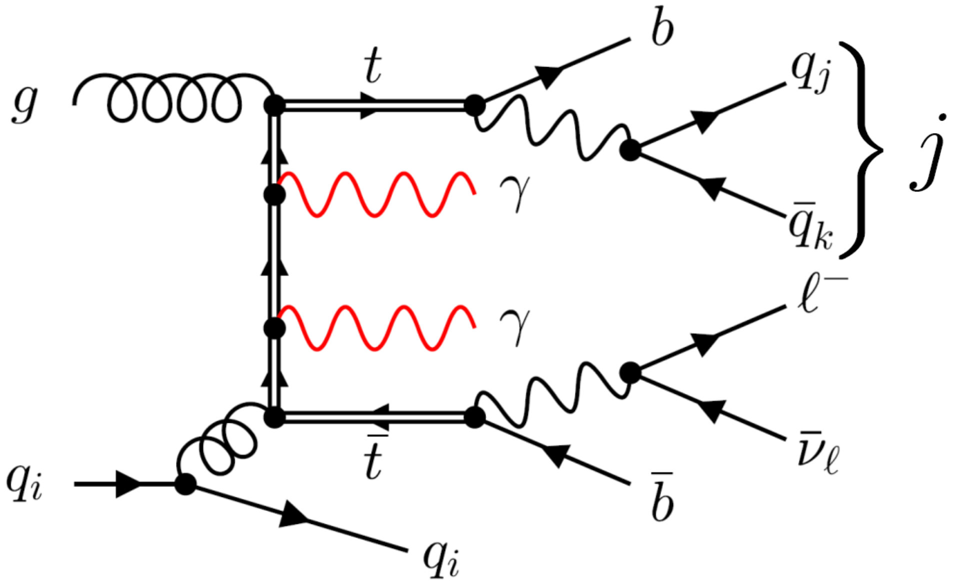
$$\sigma^{\text{NLO}}_{\text{Full}}(\epsilon_\gamma = 0.5) = 0.2832(7) \text{ fb}$$
$$\sigma^{\text{NLO}}_{\text{Full}}(E_{T\,\gamma}\,\epsilon_\gamma = 10 \text{ GeV}) = 0.2666(8) \text{ fb}$$

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

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

Integrated Fiducial cross section in lepton + jet channel





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

Differential Fiducial cross section in lepton + jet channel

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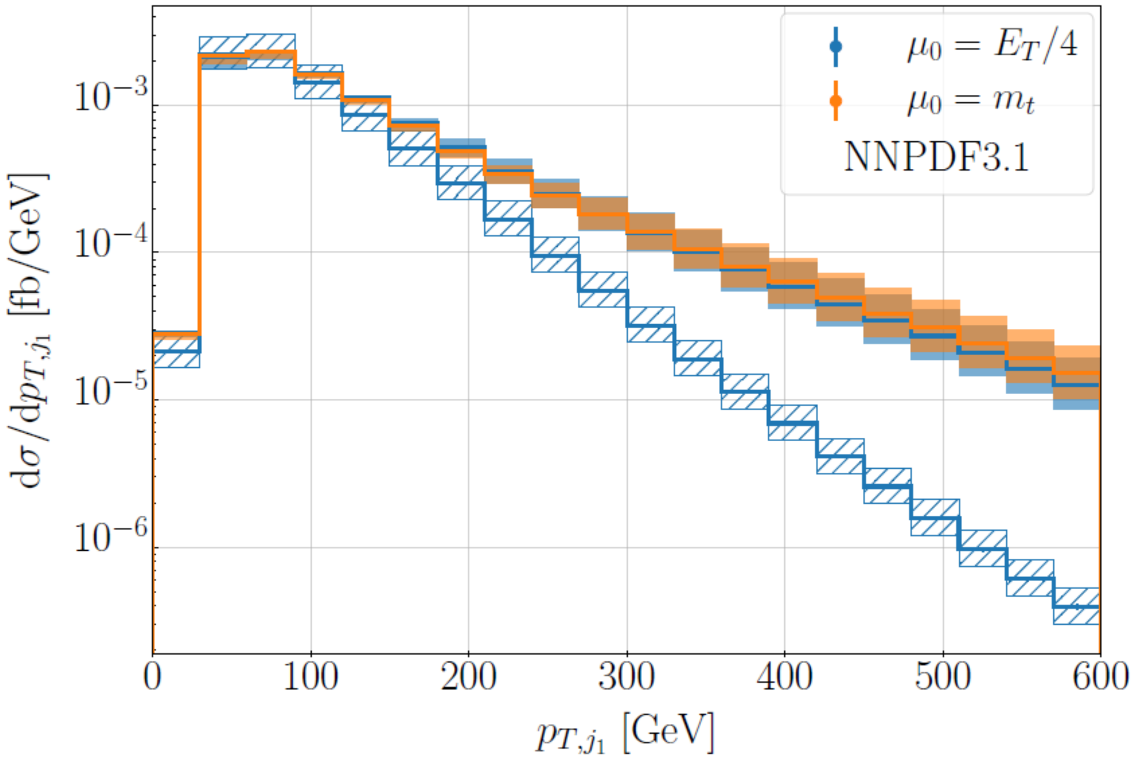

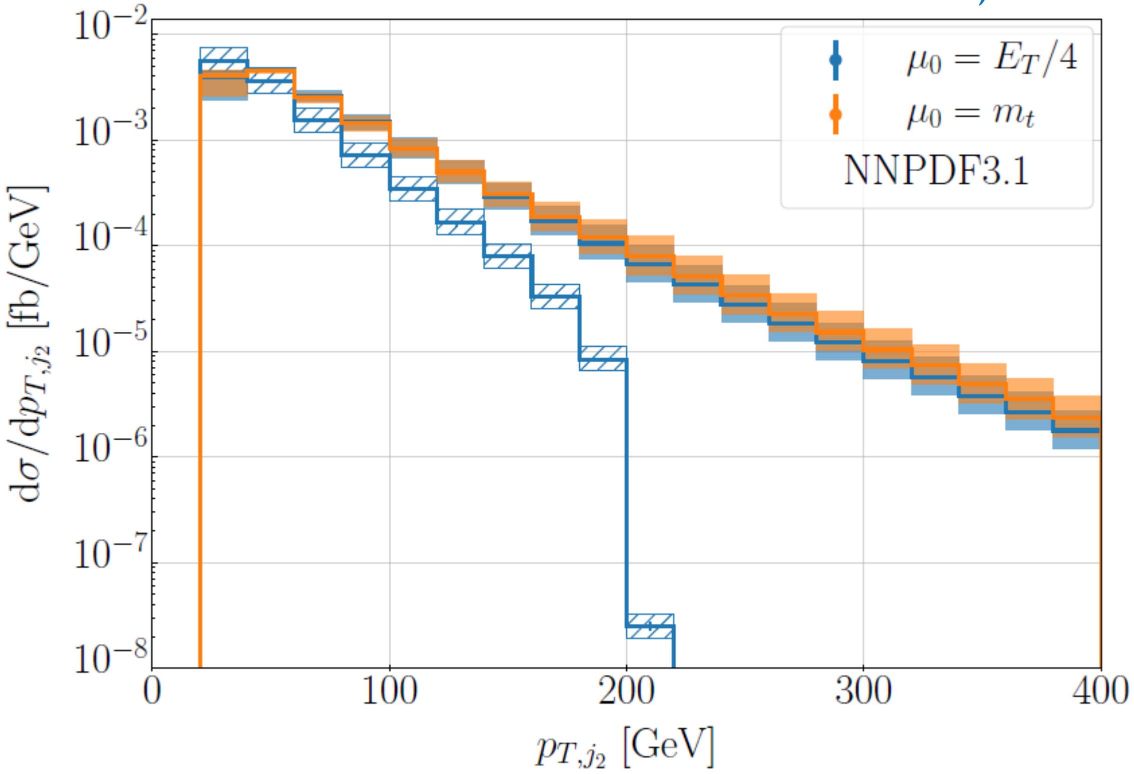

- Huge NLO QCD corrections caused by hard jets in the production stage
- Scale uncertainties in tails ~50%

- 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%

Complete NLO predictions for $pp \to t\bar{t}\gamma\gamma$ in di-lepton channel

		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

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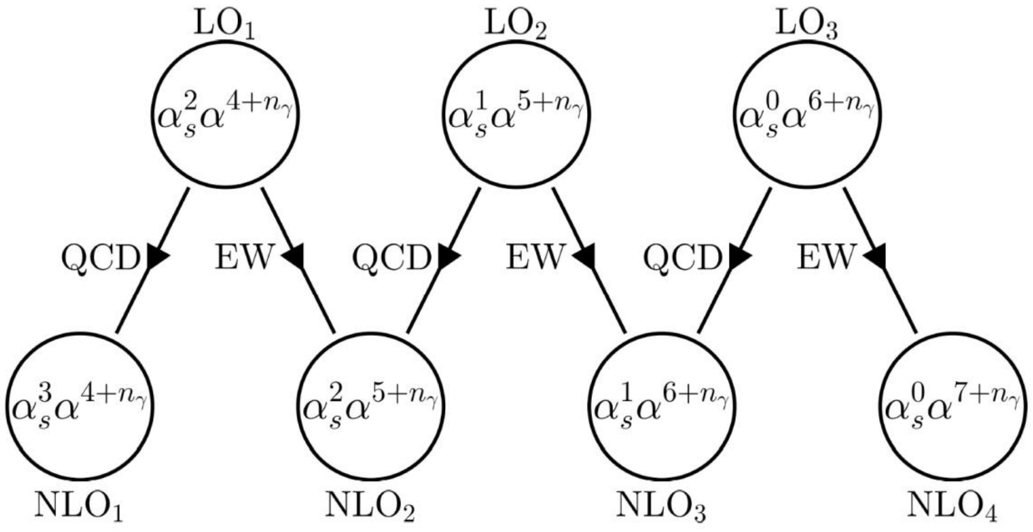
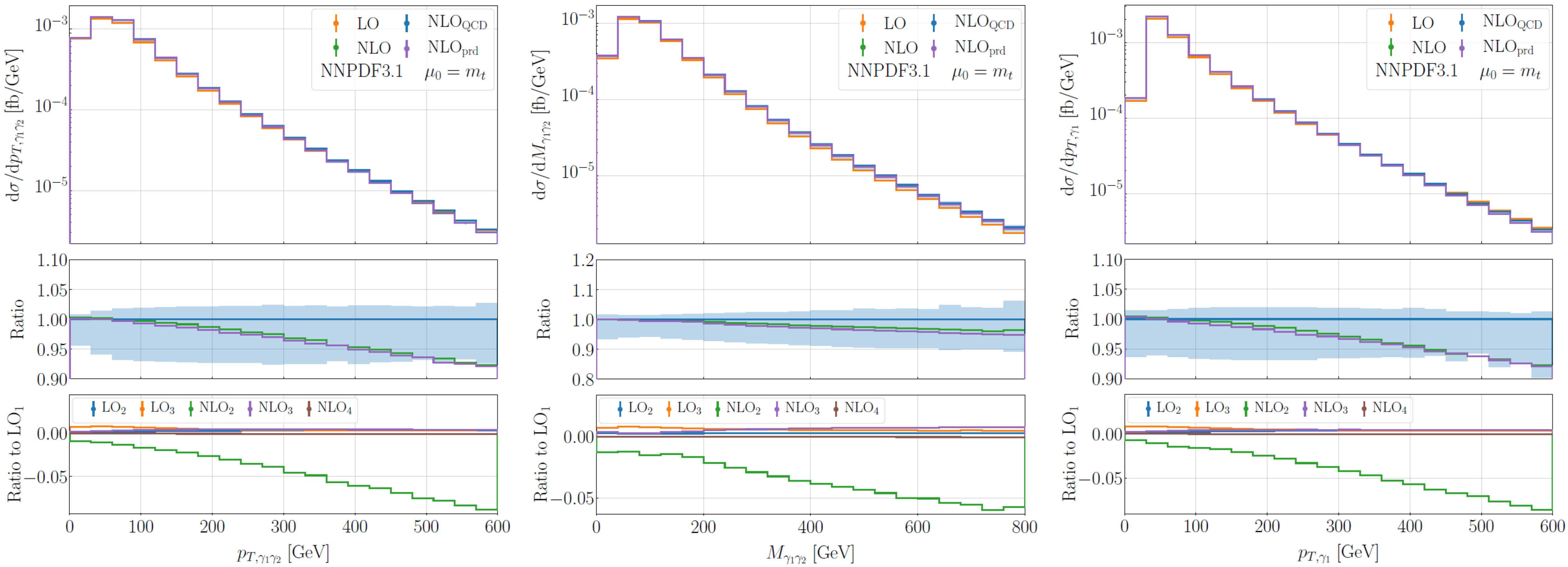


- Subleading LO contributions ~1%
- NLO corrections dominated by NLO_1
- Subleading NLO corrections ~1%

- $NLO_{prd} = LO_1 + LO_2 + LO_3 + NLO_1 + NLO_{2,prd} + NLO_{3,prd} + NLO_{4,prd}$
- No photon radiation and higer-order corrections in top-quark decays in subleading NLO contributions

Complete NLO predictions for $pp \to t\bar{t}\gamma\gamma$ in di-lepton channel

Stremmer, Worek '24



- Subleading NLO corrections as large as 10% due to EW Sudakov logarithms in NLO$_2$
- Accidental cancellations between NLO$_2$ and NLO$_3$
- Negligible differences between NLO$_{prd}$ and NLO of less than 2%