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$t\bar{t}jj$ – NLO QCD corrections to top-quark pair production and decays at the LHC

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Based on Phys. Rev. D 107 (2023) 11, 114027

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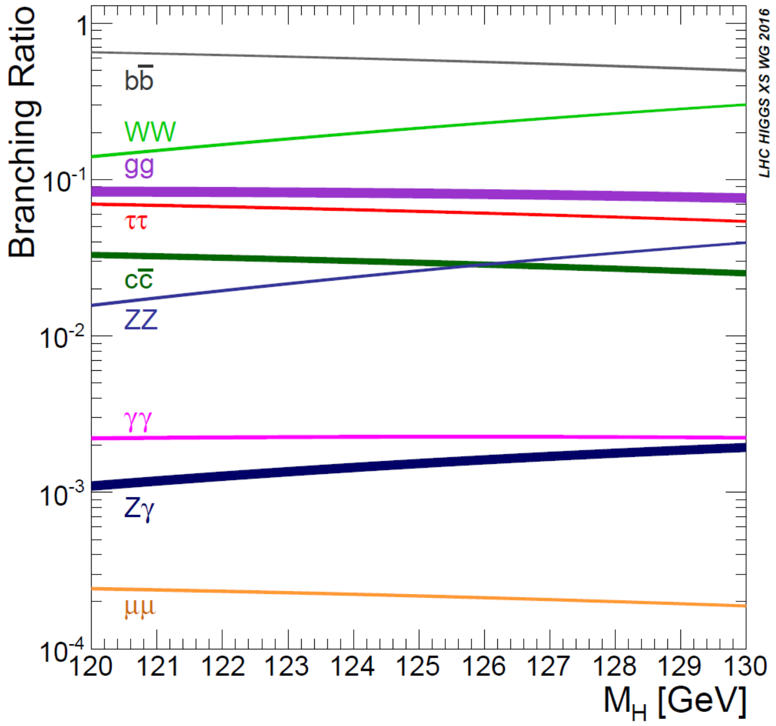
QCD@LHC 2023, Durham, UK, 6 September 2023

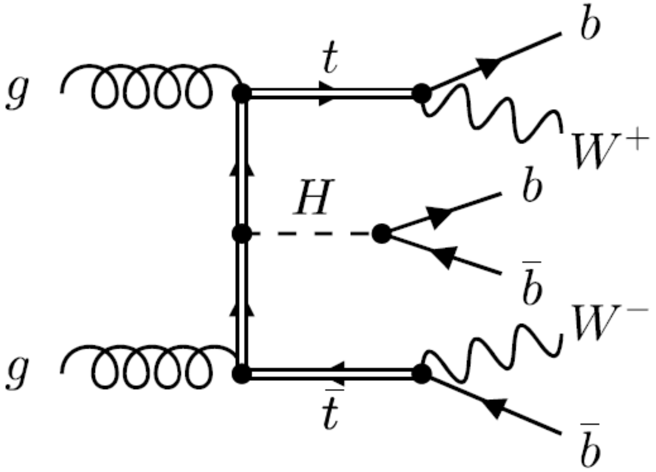
Motivation

- 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 → $b\bar{b}$ largest branching ratio with ~58%
- Large irreducible background from pp → $t\bar{t}b\bar{b}$
  & reducible one from pp → $t\bar{t}jj$

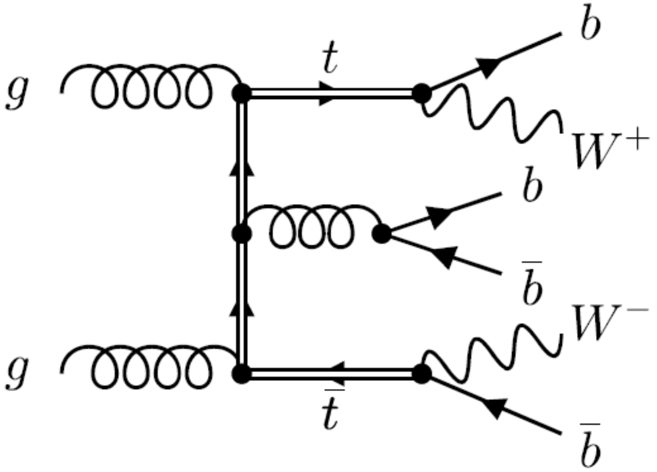
LHC HIGGS XS WG 2016



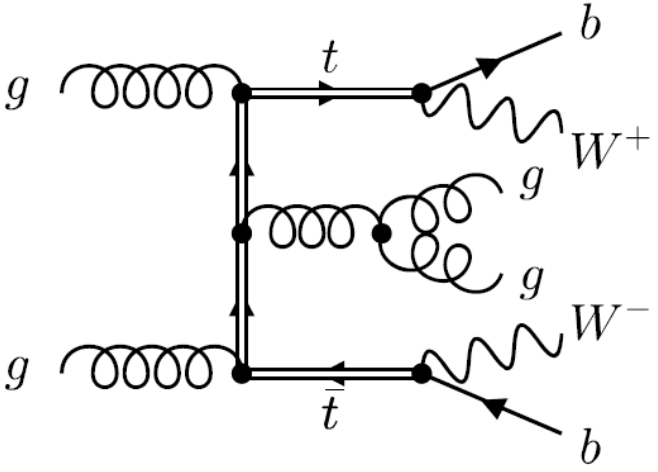
pp → $t\bar{t}H(H \to b\bar{b})$



pp → $t\bar{t}b\bar{b}$

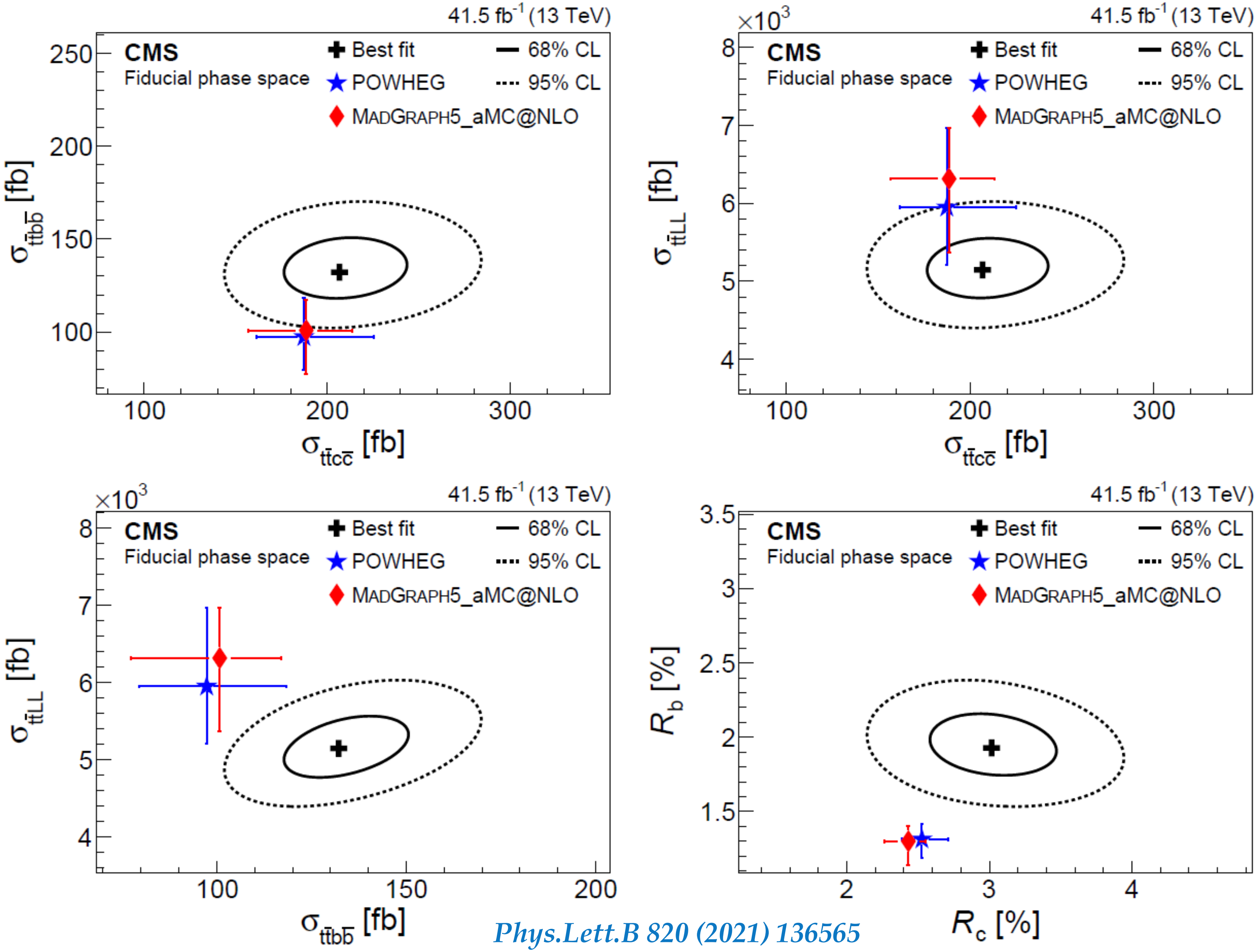


pp → $t\bar{t}jj$



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

Motivation



Phys.Lett.B 820 (2021) 136565

Cross section ratios:

- $R_b = \sigma_{t\bar{t}b\bar{b}} / \sigma_{t\bar{t}LL}$
- $R_c = \sigma_{t\bar{t}c\bar{c}} / \sigma_{t\bar{t}LL}$

- Playground for c and b jet tagging
- Better understanding of separation in different processes
- Differences between theoretical predictions and measurements up to 2.5σ for R_b

LL=light flavours and gluon jets

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

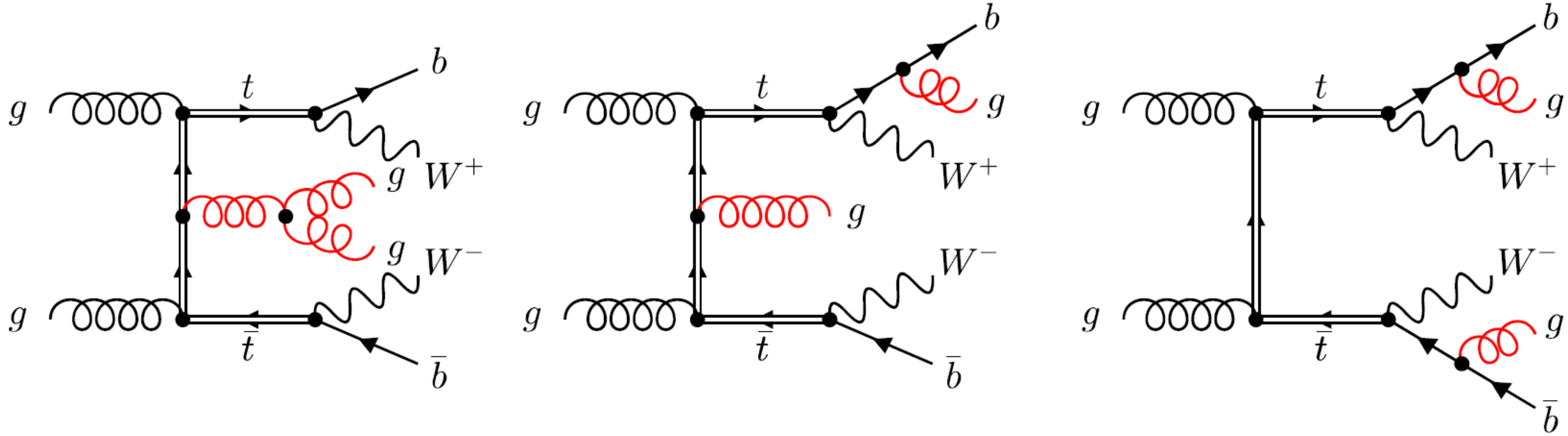
State of the art: **NLO QCD**

- Stable top quarks
  - $pp \to t\bar{t}jj$ *Bevilacqua, Czakon, Papadopoulos, Worek '10'11*
  - $pp \to t\bar{t}jjj$ (NLO & MINLO) *Höche, Maierhöfer, Moretti, Pozzorini, Siegert '17*
- Parton Shower (Multi-jet merging with MEPS@NLO in Sherpa)
  - $t\bar{t} + 0,1,2$ jets *Höche, Krauss, Maierhöfer, Pozzorini, Schönherr, Siegert '15*
  - $t\bar{t} + 0,1$ jet (NLO QCD + $\mathrm{EW_{virt}}$), $t\bar{t} + 2,3,4$ jets (LO) *Gütschow, Lindert, Schönherr '18*

Setup

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

- LHC with $\sqrt{s} = 13$ TeV
- Calculation performed in Narrow Width Approximation preserving spin correlations
- Jet radiation 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

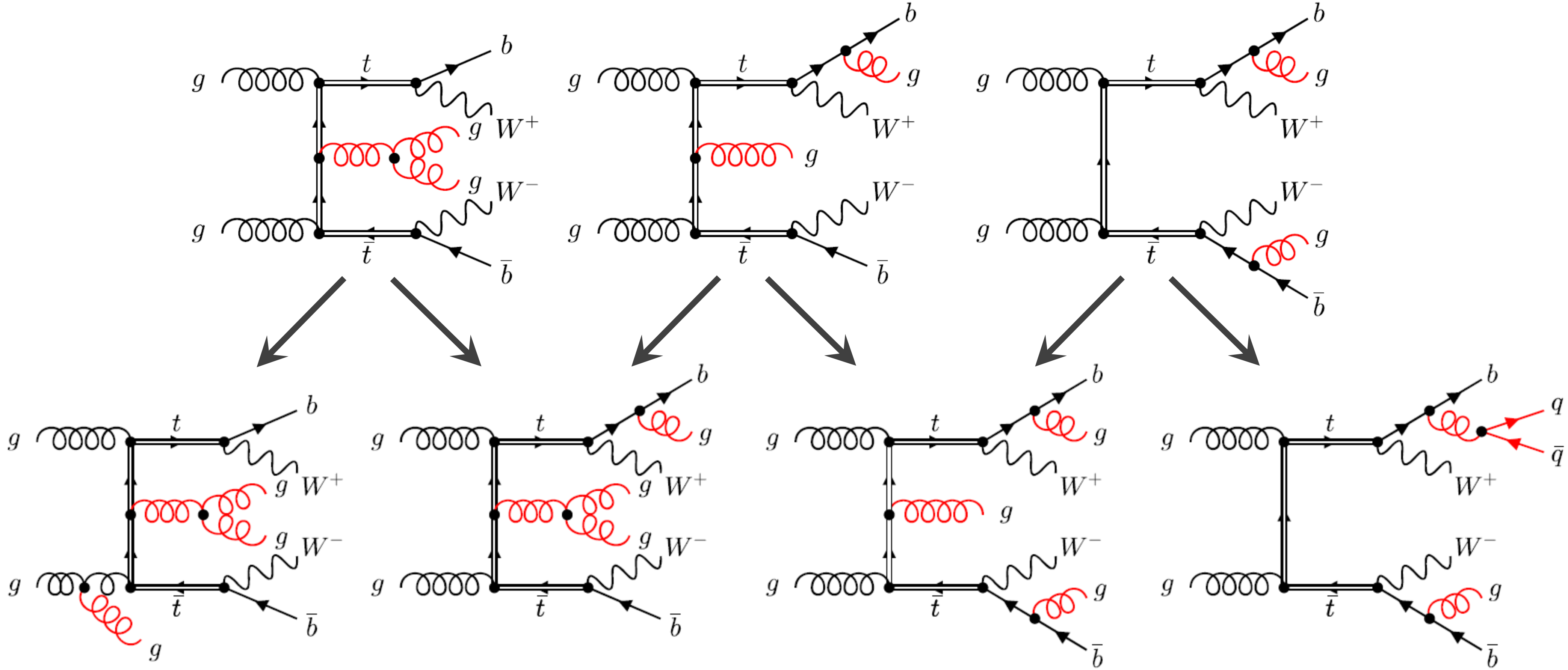


Process definition

$$d\sigma^{\mathrm{LO}}_{t\bar{t}jj} = \Gamma_t^{-2}\Big(\underbrace{d\sigma^{\mathrm{LO}}_{t\bar{t}jj}\, d\Gamma^{\mathrm{LO}}_{t\bar{t}}}_{\text{Prod.}} + \underbrace{d\sigma^{\mathrm{LO}}_{t\bar{t}j}\, d\Gamma^{\mathrm{LO}}_{t\bar{t}j}}_{\text{Mix}} + \underbrace{d\sigma^{\mathrm{LO}}_{t\bar{t}}\, d\Gamma^{\mathrm{LO}}_{t\bar{t}jj}}_{\text{Decay}}\Big)$$

LO

NLO



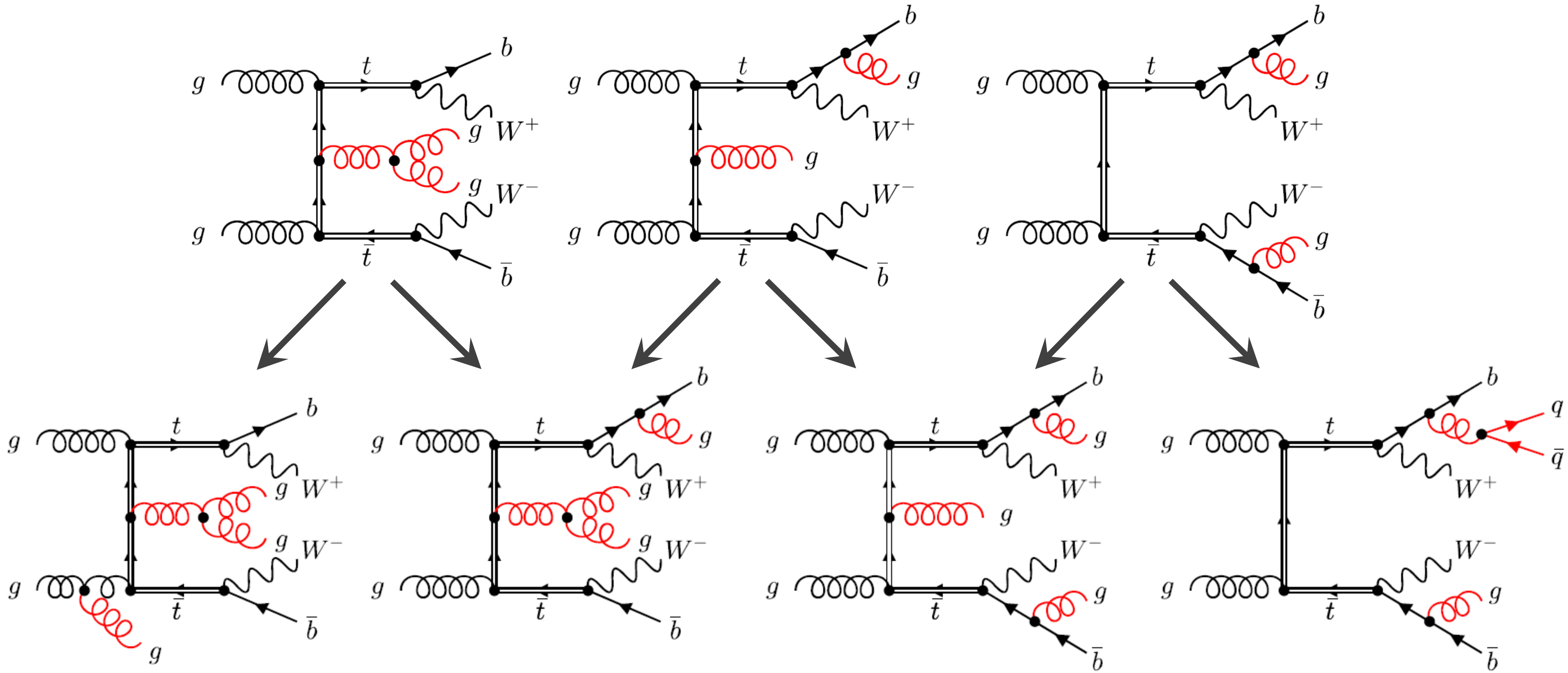
Process definition

$$d\sigma^{\mathrm{NLO}}_{t\bar{t}jj} = \Gamma_t^{-2}\Big(\overbrace{\big(d\sigma^{\mathrm{LO}}_{t\bar{t}jj} + d\sigma^{\mathrm{virt}}_{t\bar{t}jj} + d\sigma^{\mathrm{real}}_{t\bar{t}jjj}\big)\; d\Gamma^{\mathrm{LO}}_{t\bar{t}}}^{\text{Prod.}} + \overbrace{d\sigma^{\mathrm{LO}}_{t\bar{t}}\;\big(d\Gamma^{\mathrm{LO}}_{t\bar{t}jj} + d\Gamma^{\mathrm{virt}}_{t\bar{t}jj} + d\Gamma^{\mathrm{real}}_{t\bar{t}jjj}\big)}^{\text{Decay}}$$

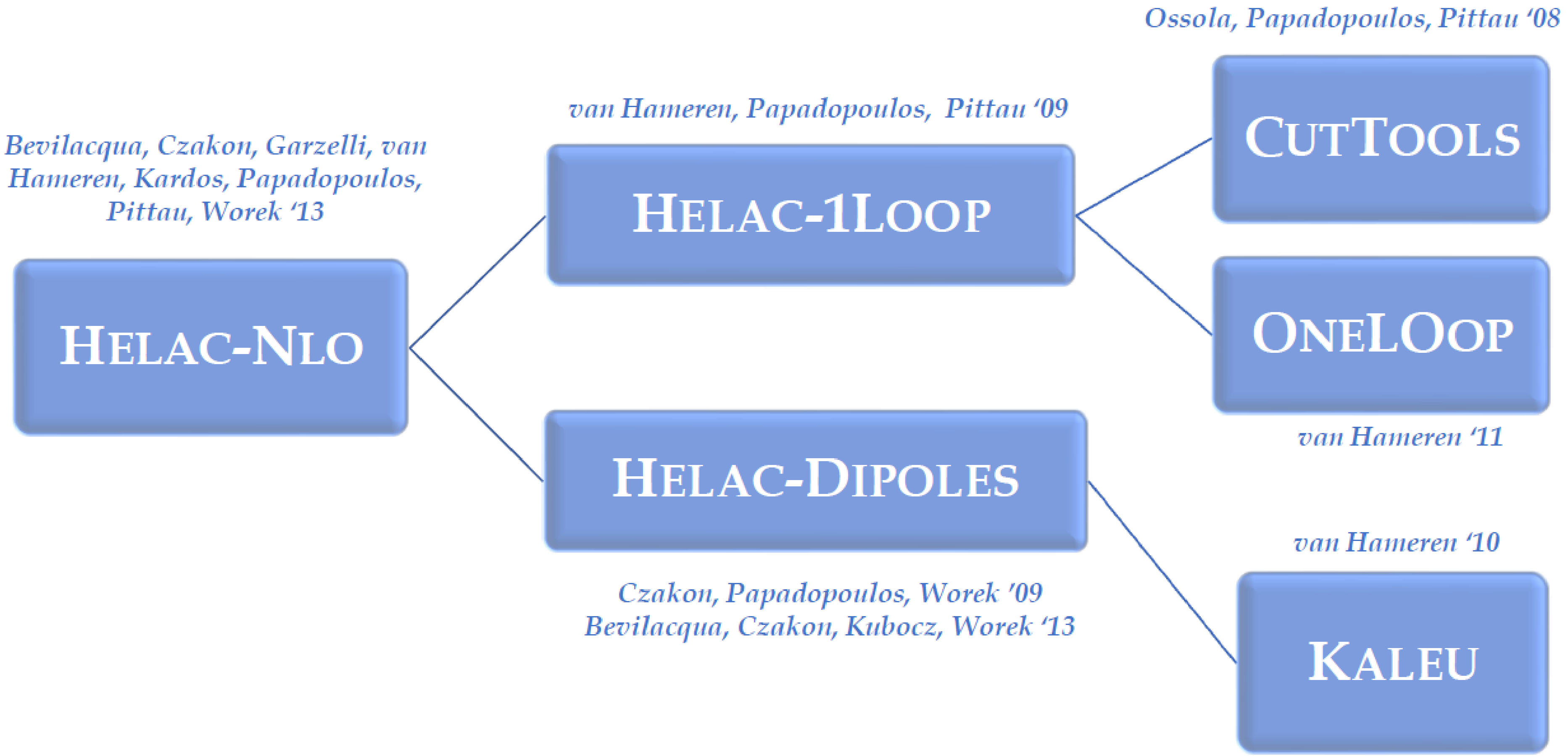
$$\underbrace{+\, d\sigma^{\mathrm{LO}}_{t\bar{t}j}\, d\Gamma^{\mathrm{LO}}_{t\bar{t}j} + d\sigma^{\mathrm{LO}}_{t\bar{t}jj}\, d\Gamma^{\mathrm{virt}}_{t\bar{t}} + d\sigma^{\mathrm{virt}}_{t\bar{t}}\, d\Gamma^{\mathrm{LO}}_{t\bar{t}jj} + d\sigma^{\mathrm{virt}}_{t\bar{t}j}\, d\Gamma^{\mathrm{LO}}_{t\bar{t}j} + d\sigma^{\mathrm{LO}}_{t\bar{t}j}\, d\Gamma^{\mathrm{virt}}_{t\bar{t}j} + d\sigma^{\mathrm{real}}_{t\bar{t}jj}\, d\Gamma^{\mathrm{real}}_{t\bar{t}j} + d\sigma^{\mathrm{real}}_{t\bar{t}j}\, d\Gamma^{\mathrm{real}}_{t\bar{t}jj}}_{\text{Mix}}\Big)$$

LO

NLO



Computational framework



- Theoretical prediction are stored in modified Les Houches Event Files (LHEFs) and ROOT Ntuples
- Reweighting to different renormalisation/factorisation scales and PDF sets

Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre '14

Validation

Virtual Corrections

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

Real Corrections in Helac-Dipoles

- Catani-Seymour subtraction *Catani, Seymour '97* *Catani, Dittmaier, Seymour, Trocsanyi '02*
  - Additional polarised subtraction terms
  - $\mathrm{t} \to W^+ bg$ *Campbell, Ellis, Tramontano '04 (unpolarised)*
  - $\mathrm{t} \to W^+ bgg$ *Melnikov, Scharf, Schulze '12 (unpolarised)*
  - $\mathrm{t} \to W^+ bq\bar{q}$
- Nagy-Soper subtraction *Bevilacqua, Czakon, Kubocz, Worek '13*
  - Extended to radiative decays

Setup of the calculation

- Exclusive in $n_b = 2$, inclusive in $n_j \geq 2$
- Anti-k_T jet algorithm ($R = 0.4$) *Cacciari, Salam, Soyez '08*
- Event selection: *CMS-PAS-TOP-20-006*

$$p_{T,\ell} > 20 \text{ GeV}\,, \quad |y_\ell| < 2.4\,, \quad \Delta R_{\ell\ell} > 0.4\,, \quad M_{\ell\ell} > 20 \text{ GeV}\,,$$

$$p_{T,b} > 30 \text{ GeV}\,, \quad |y_b| < 2.4\,, \quad \Delta R_{bb} > 0.4\,,$$

$$p_{T,j} > 40 \text{ GeV}\,, \quad |y_j| < 2.4\,, \quad \Delta R_{jj} > 0.4\,,$$

$$\Delta R_{bl} > 0.4\,, \quad \Delta R_{jl} > 0.4\,, \quad \Delta R_{jb} > 0.8$$

- Renormalisation/Factorisation scale: $\mu_R = \mu_F = \mu_0 = \frac{H_T}{2}$ $\quad H_T = \sum_{i=1}^{2} p_{T\ell_i} + \sum_{i=1}^{2} p_{Tj_i} + \sum_{i=1}^{2} p_{Tb_i} + p_T^{miss}$
- NNPDF3.1 NLO PDF set with $\alpha_s = 0.118$ *Ball et. al. '17*

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$$\Delta R_{bl} > 0.4\,, \quad \Delta R_{jl} > 0.4\,, \quad \Delta R_{jb} > 0.8\,(0.4)$$

- Renormalisation/Factorisation scale: $\mu_R = \mu_F = \mu_0 = \frac{H_T}{2}$ $\quad H_T = \sum_{i=1}^{2} p_{T\ell_i} + \sum_{i=1}^{2} p_{Tj_i} + \sum_{i=1}^{2} p_{Tb_i} + p_T^{miss}$
- NNPDF3.1 NLO PDF set with $\alpha_s = 0.118$ *Ball et. al. '17*

Integrated Fiducial cross section

$$\Delta R_{jb} > 0.8$$

i	σ^{LO} [fb]	σ^{NLO} [fb]	$\sigma_i^{\mathrm{LO}}/\sigma_{\mathrm{Full}}^{\mathrm{LO}}$	$\sigma_i^{\mathrm{NLO}}/\sigma_{\mathrm{Full}}^{\mathrm{NLO}}$
Full	$868.8(2)^{+60\%}_{-35\%}$	$1225(1)^{+1\%}_{-14\%}$	1.00	1.00
Prod.	$843.2(2)^{+60\%}_{-35\%}$	$1462(1)^{+12\%}_{-19\%}$	0.97	1.19
Mix	25.465(5)	−236(1)	0.029	−0.19
Decay	0.2099(1)	0.1840(8)	0.0002	0.0002

- $\mathcal{K} = \sigma_{\mathrm{Full}}^{\mathrm{NLO}}/\sigma_{\mathrm{Full}}^{\mathrm{LO}} = 1.41$
- Scale uncertainties reduced from 60% to 14%
- Dominated by Prod.

- LO cross section

$$\sigma_{gg}^{\mathrm{LO}} = 561.1(2)\ \mathrm{fb} \quad (65\%)$$
$$\sigma_{gq}^{\mathrm{LO}} = 272.6(1)\ \mathrm{fb} \quad (31\%)$$
$$\sigma_{qq'}^{\mathrm{LO}} = 35.10(1)\ \mathrm{fb} \quad (4\%)$$

- Internal PDF uncertainties

NNPDF3.1: $\sigma^{\mathrm{NLO}} = 1225(1)^{+1.3\%}_{-1.3\%}$ fb

MSHT20: $\sigma^{\mathrm{NLO}} = 1212(1)^{+2.1\%}_{-1.8\%}$ fb

CT18: $\sigma^{\mathrm{NLO}} = 1197(1)^{+2.9\%}_{-2.7\%}$ fb

Integrated Fiducial cross section

$$\Delta R_{jb} > 0.8$$

i	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [fb]	$\sigma_i^{\rm LO}/\sigma_{\rm Full}^{\rm LO}$	$\sigma_i^{\rm NLO}/\sigma_{\rm Full}^{\rm NLO}$
Full	$868.8(2)^{+60\%}_{-35\%}$	$1225(1)^{+1\%}_{-14\%}$	1.00	1.00
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$$\sigma^{\rm NLO}_{\rm Prod.LOdecay} = \left(\frac{\Gamma_t^{\rm NLO}}{\Gamma_t^{\rm LO}}\right)^2 \sigma^{\rm NLO}_{\rm Prod.} = 1221(1)^{+12\%}_{-19\%}$$

$$\Delta R_{jb} > 0.4$$

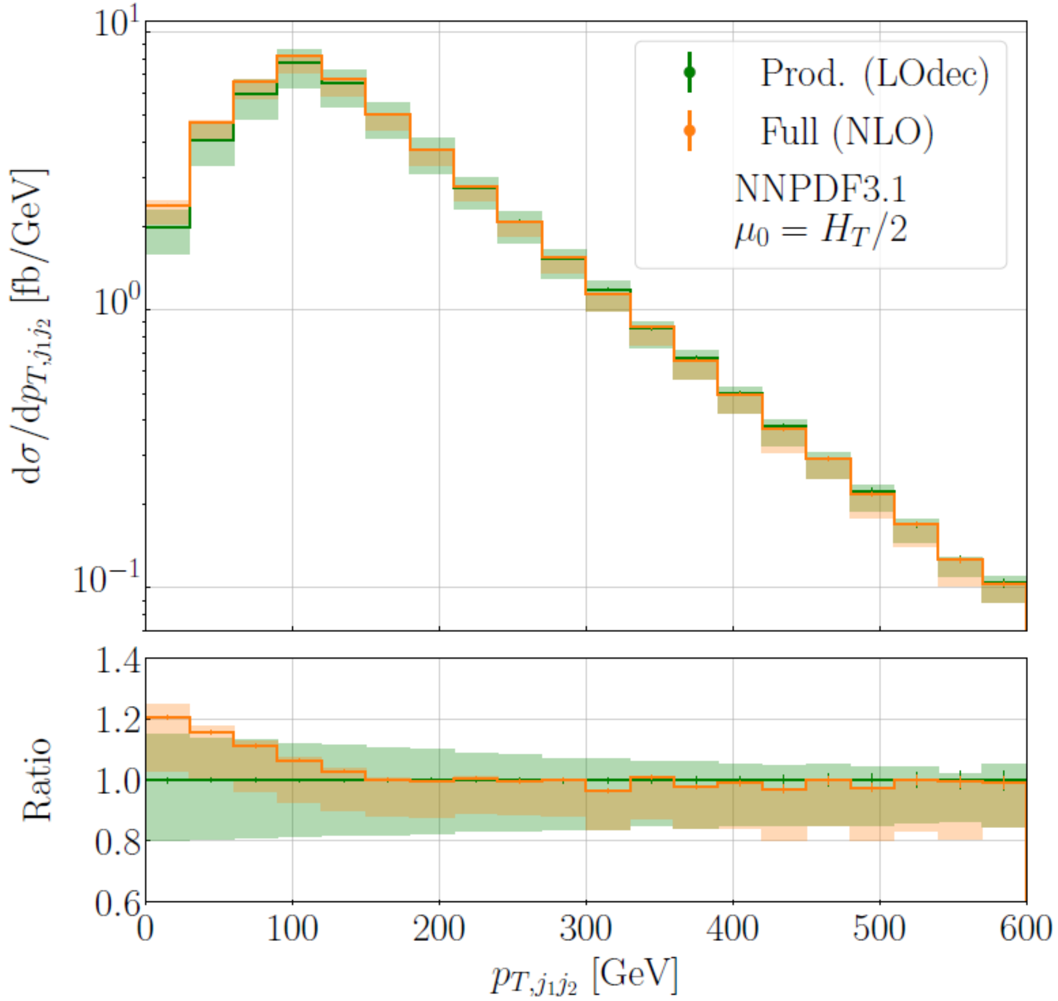
i	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [fb]	$\sigma_i^{\rm LO}/\sigma_{\rm Full}^{\rm LO}$	$\sigma_i^{\rm NLO}/\sigma_{\rm Full}^{\rm NLO}$
Full	$1074.5(3)^{+60\%}_{-35\%}$	$1460(1)^{+1\%}_{-13\%}$	1.00	1.00
Prod.	$983.1(3)^{+60\%}_{-35\%}$	$1662(1)^{+11\%}_{-18\%}$	0.91	1.14
Mix	89.42(3)	−205(1)	0.083	−0.14
Decay	1.909(1)	2.436(6)	0.002	0.002

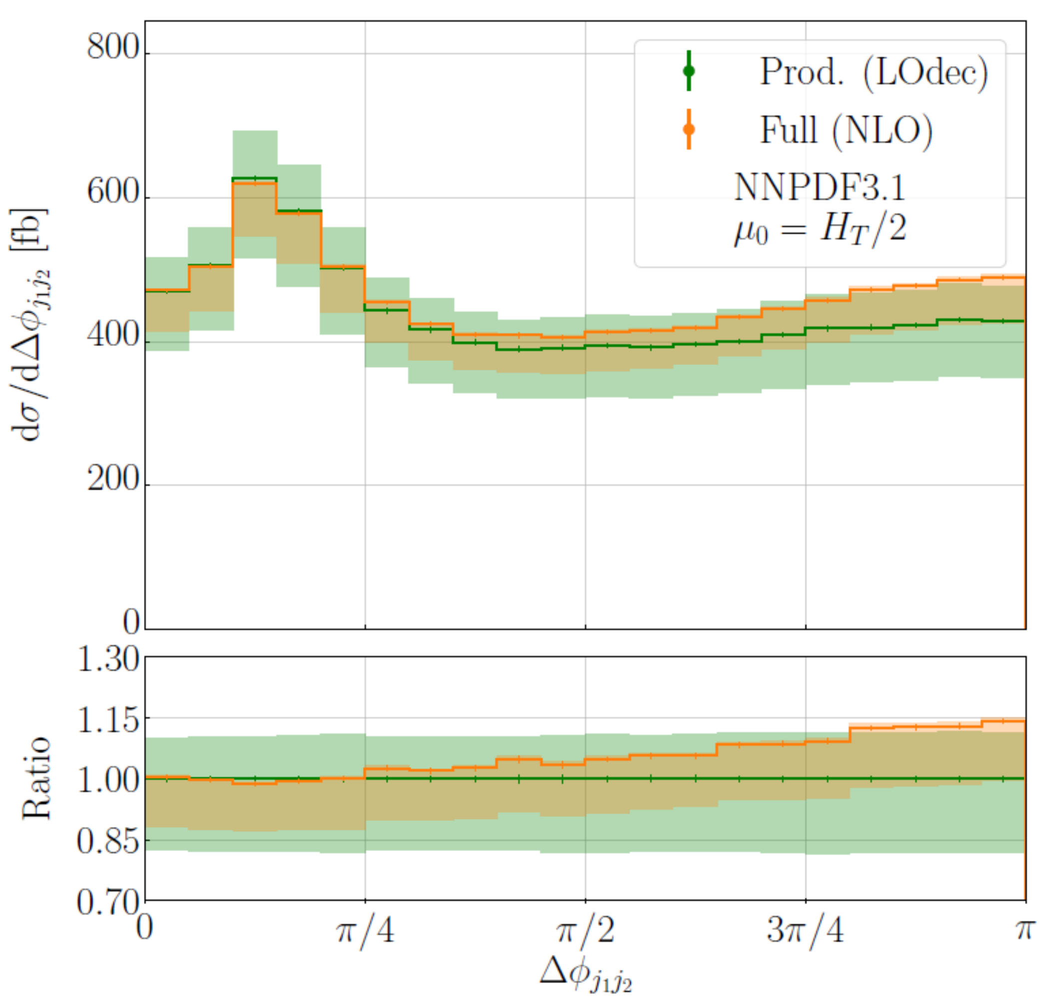
$$\sigma^{\rm NLO}_{\rm Prod.LOdecay} = 1390(2)^{+11\%}_{-18\%}$$

- LO: Prod. increased by 16%, Mix increased by 250%, Decay increased by 810%
- NLO: Relative size of Mix decreased
- Differences up to 5% for Prod. LOdecay, scale uncertainties reduced by 5%

Differential Fiducial cross section

$\Delta R_{jb} > 0.4$



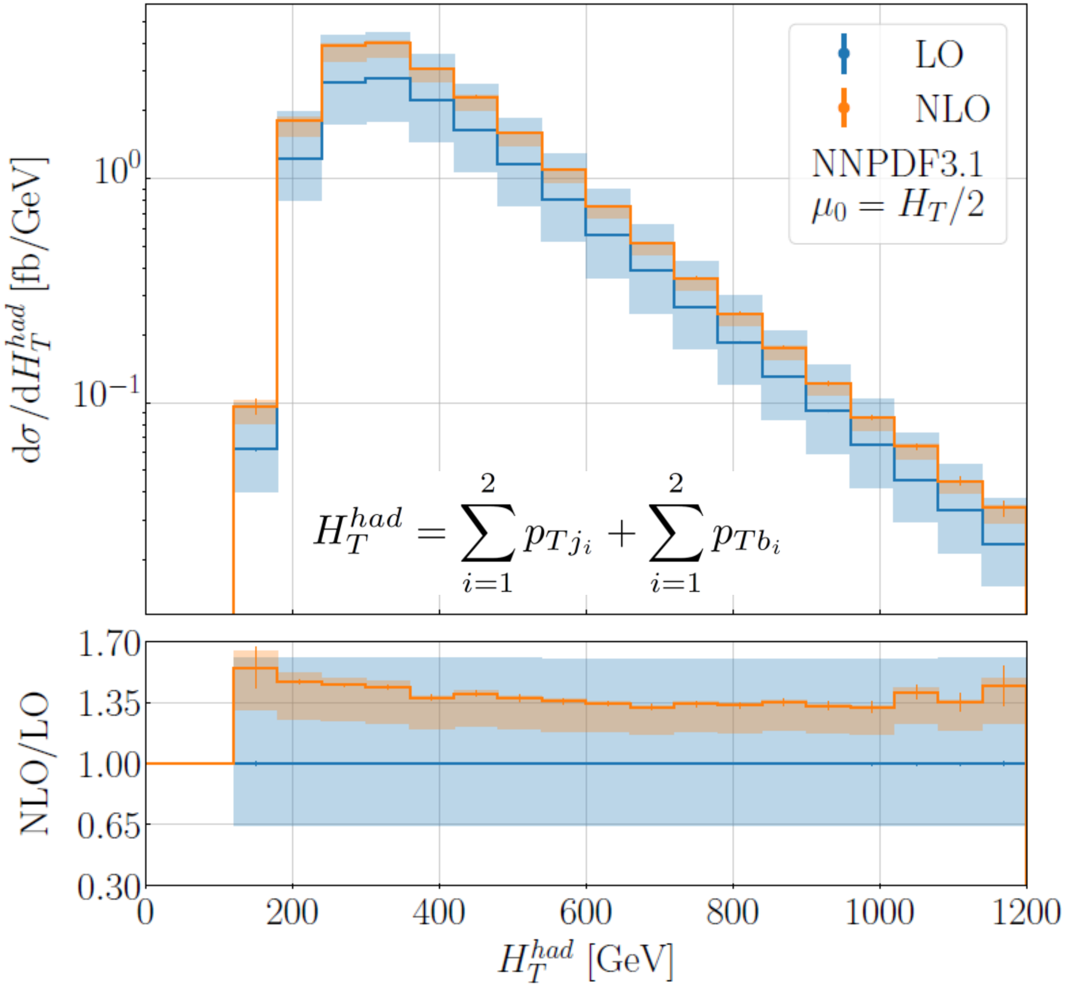


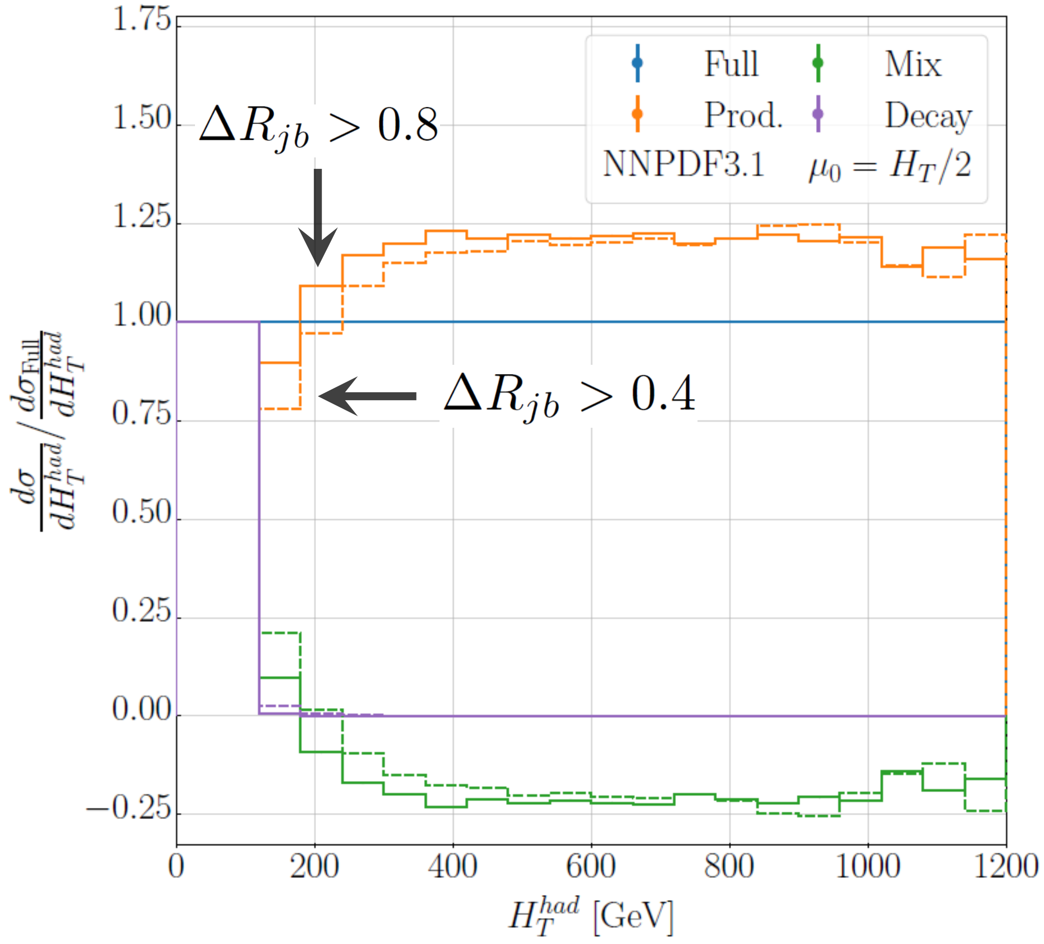
- Shape distortions up to 20%
- Scale uncertainties reduced by 5% below 300 GeV

- Shape distortions up to 15%
- Scale uncertainties reduced by 5%

Differential Fiducial cross section

$\Delta R_{jb} > 0.8$

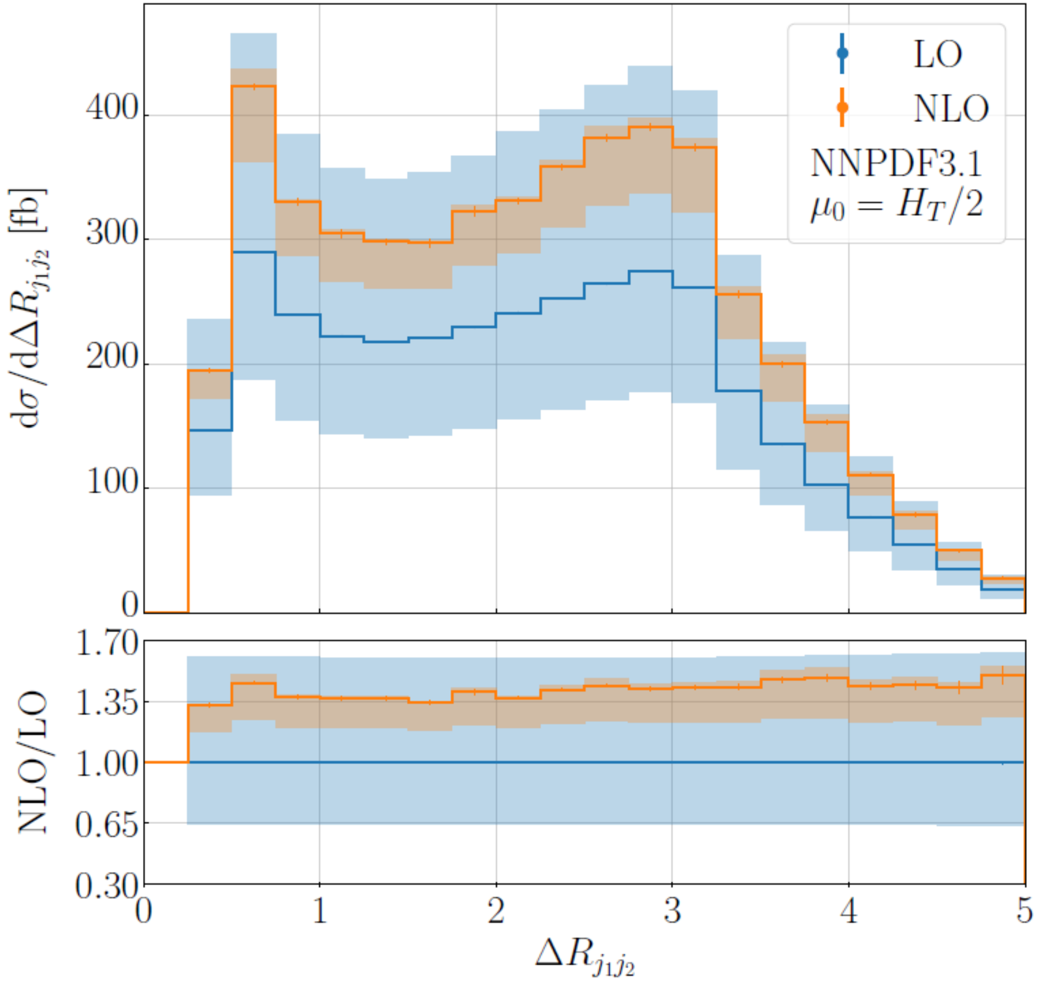


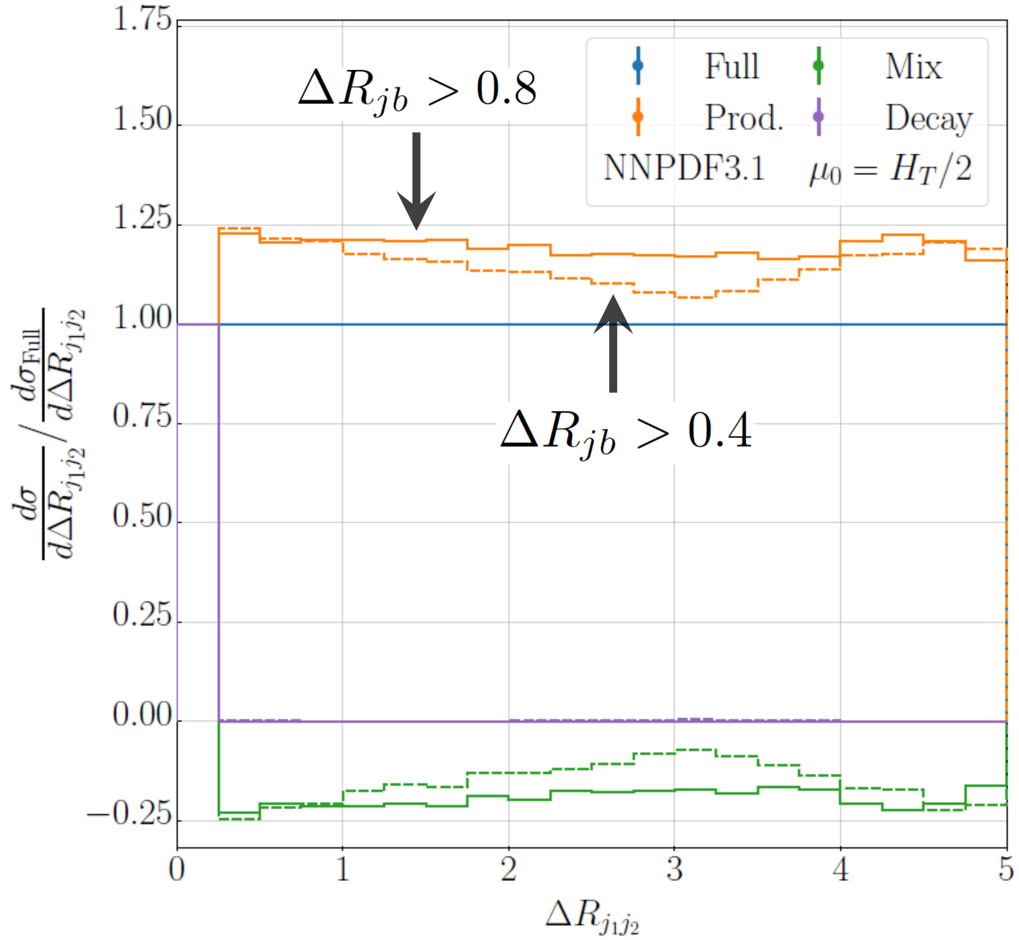


- NLO QCD corrections ~30% – 60%
- Scale uncertainties reduced from 60% to 15%
- Mix/Full [−25%, 20%]
- Mix sensitive to ΔR_{jb} at small energies

Differential Fiducial cross section

$\Delta R_{jb} > 0.8$

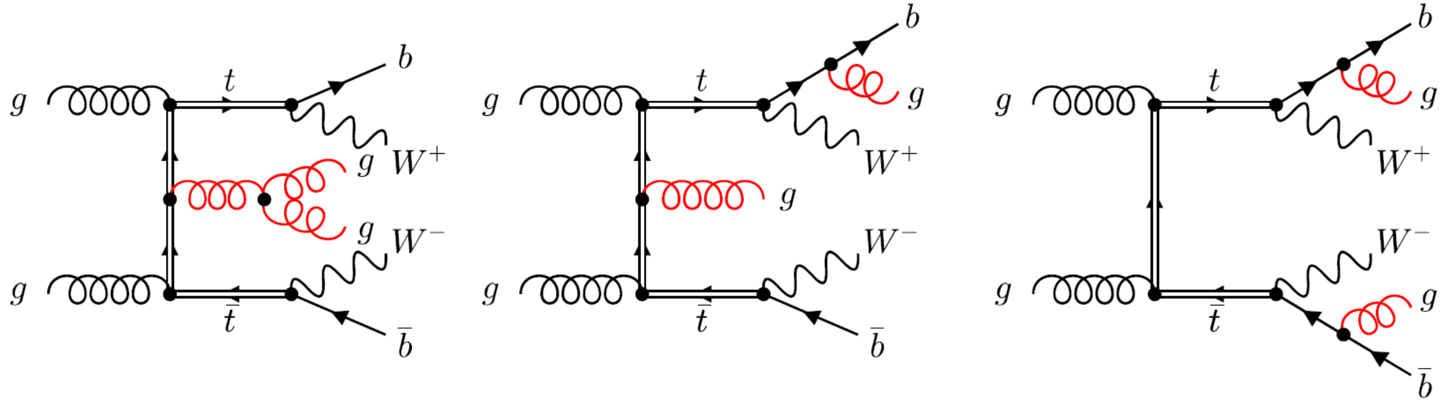




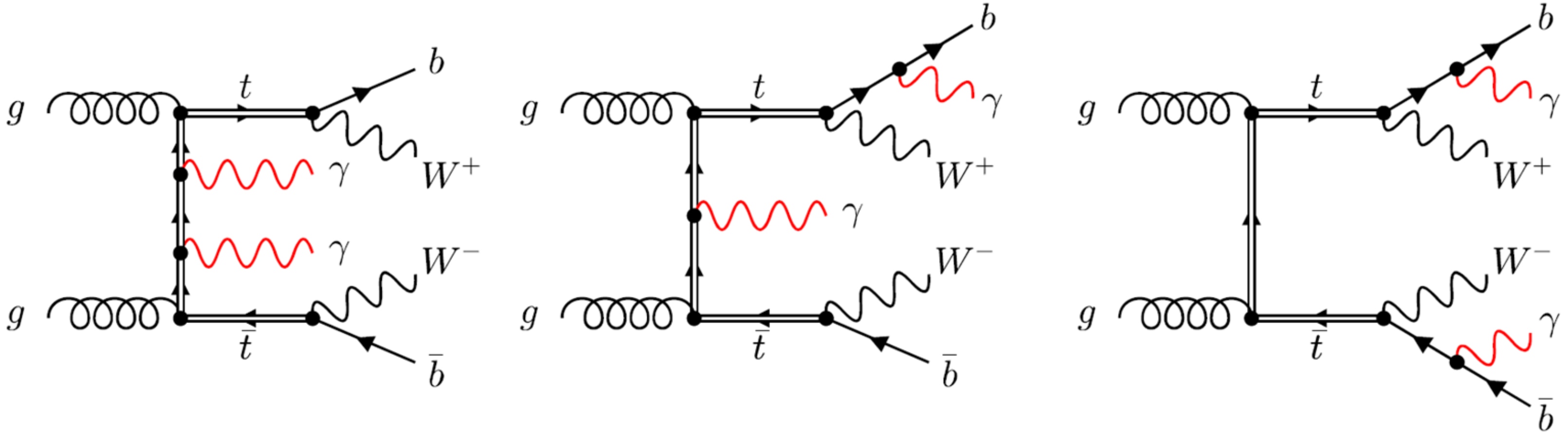
- NLO QCD corrections ~30% – 50%
- Scale uncertainties reduced from 60% to 15%
- Mix/Full [−25%, −7%]
- Larger shape distortions for $\Delta R_{jb} > 0.4$

From tt̄jj to tt̄γγ

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



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

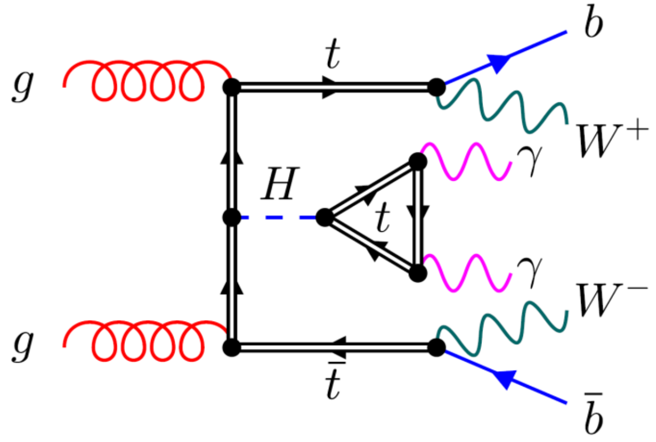


What are the similarities/differences between both processes?

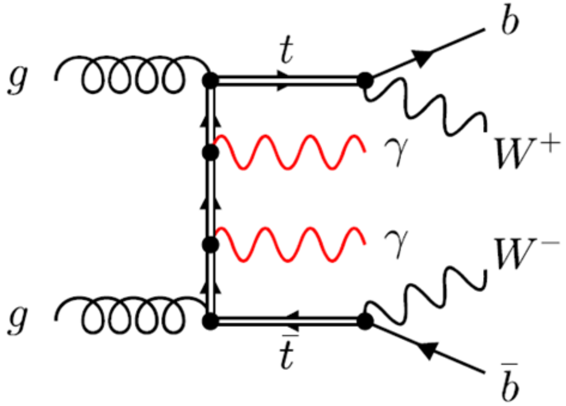
Resonant contributions in $t\bar{t}\gamma\gamma$

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

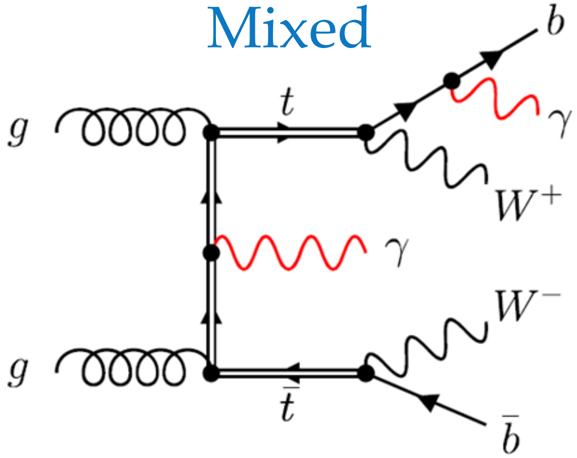
- Irreducible background of $pp \to t\bar{t}H(H \to \gamma\gamma)$
- Photon bremsstrahlung in $t\bar{t}$ production and t / W decays
- No mixing of resonant contributions at NLO QCD
- Similar setup as $t\bar{t}jj$



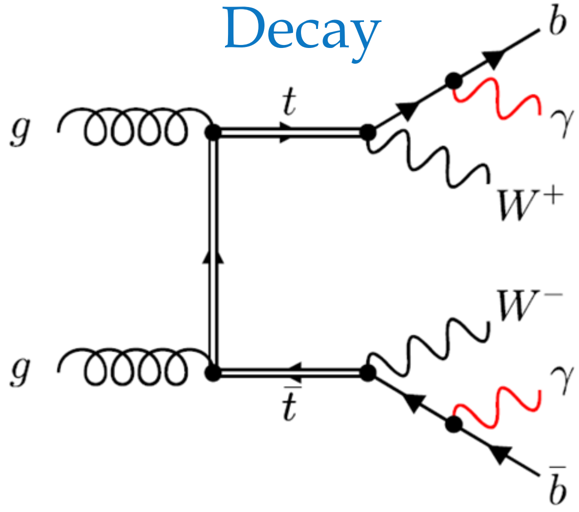
Prod.



Mixed

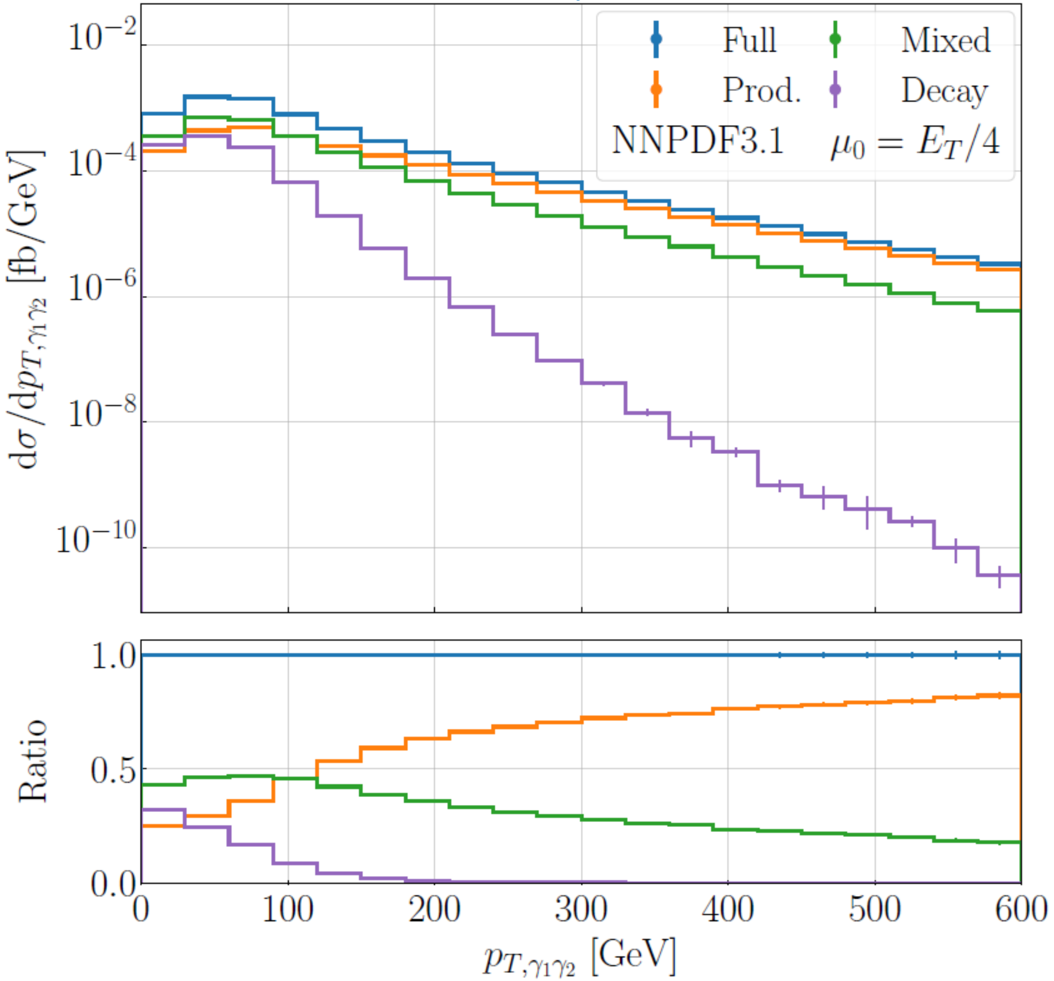


Decay

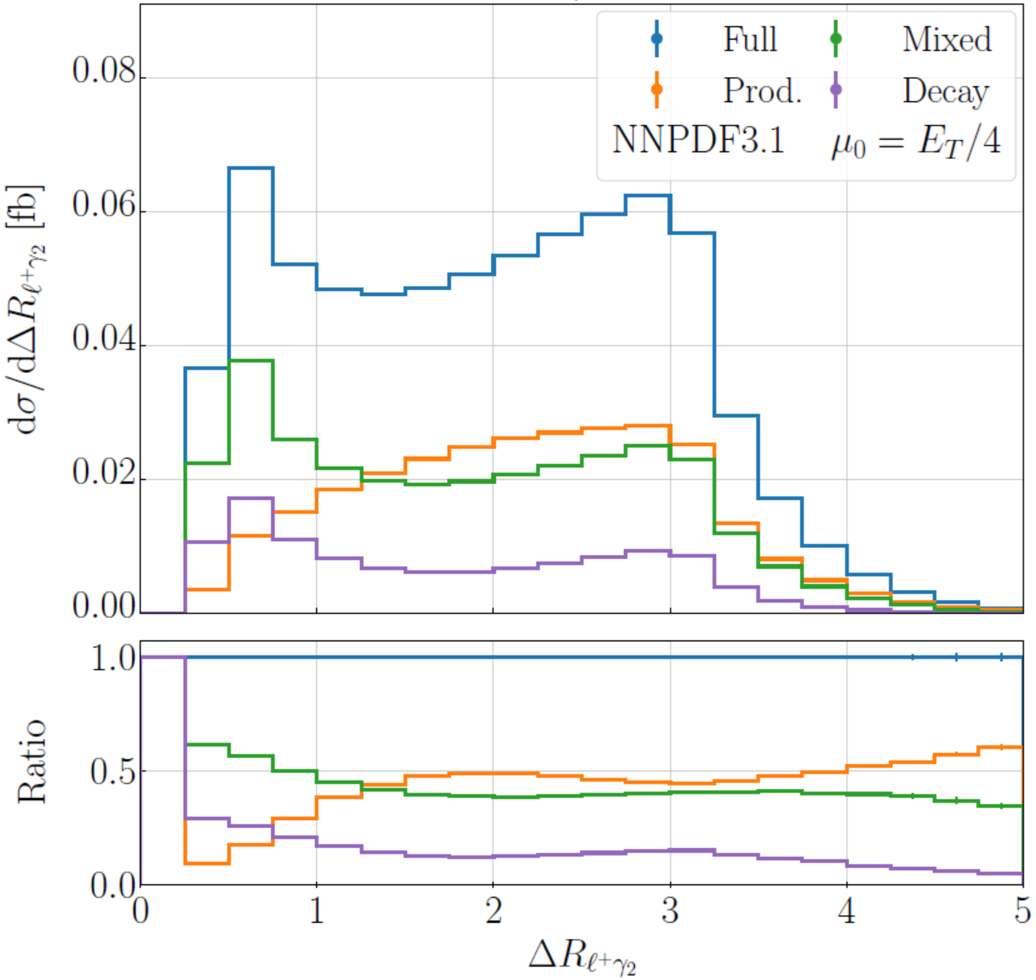


Resonant contributions in $t\bar{t}\gamma\gamma$

Stremmer, Worek, JHEP 08 (2023) 179



Stremmer, Worek, JHEP 08 (2023) 179



- Large contribution from photon emission in decays
- Prod. dominant at large p_T (~80% of Full)
- Different peak structures for Prod., Mixed and Decay

Resonant contributions in $t\bar{t}\gamma\gamma$

Stremmer, Worek, JHEP 08 (2023) 179

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

- Only ~39% of Full from Prod.
- gg channel supressed for increasing number of photons in $t\bar{t}$ production
- Conclusions also hold in lepton + jet top-quark decay channel

Conclusion

- NLO QCD corrections to $pp \to t\bar{t}(jj) \to W^+W^-b\bar{b}jj \to \ell^+\ell^-\,\nu_\ell\bar{\nu}_\ell\,b\bar{b}\,jj$
- Jet radiation consistenly included in production and decay of top-quark pair
- LO dominated by Prod., Mix and Decay contributions negligible at LO
- Mixing of different resonant contributions at NLO QCD
- Different sign of Mix contribution at NLO
- Theoretical uncertainties dominated by scale uncertainties
- Large contributions from photon bremsstrahlung in t / W decays

Outlook

- Cross section ratios $R_b = \sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$ and $R_c = \sigma_{t\bar{t}c\bar{c}}/\sigma_{t\bar{t}jj}$ in fiducial phase space
- Hadronic W boson decays → lepton + jet top-quark decay channel

Backup

Fiducial cross section ratios

$$\Delta R_{jb} > 0.8$$

$\mathcal{R}_n$	$\mathcal{R}^{\rm LO}$	$\mathcal{R}^{\rm NLO}$	$\mathcal{R}^{\rm NLO}_{\rm exp}$
$\mathcal{R}_1 = \sigma_{t\bar{t}j}/\sigma_{t\bar{t}}$	$0.3686\,^{+12\%}_{-10\%}$	$0.3546\,^{+0\%}_{-5\%}$	$0.3522\,^{+0\%}_{-3\%}$
$\mathcal{R}_2 = \sigma_{t\bar{t}jj}/\sigma_{t\bar{t}j}$	$0.2539\,^{+11\%}_{-9\%}$	$0.2660\,^{+0\%}_{-5\%}$	$0.2675\,^{+0\%}_{-2\%}$

$$\mathcal{R}^{\rm NLO}_{\rm exp} = \frac{\sigma^0_{t\bar{t}j(j)}}{\sigma^0_{t\bar{t}(j)}}\left(1 + \frac{\sigma^1_{t\bar{t}j(j)}}{\sigma^0_{t\bar{t}j(j)}} - \frac{\sigma^1_{t\bar{t}(j)}}{\sigma^0_{t\bar{t}(j)}}\right)$$

- NLO QCD corrections $\sim 4\% - 5\%$
- Reduced scale uncertainties by consistent expansion in α_s from 5% to $2\% - 3\%$
- PDF uncertainties with NNPDF3.1 $\sim 0.5\%$

Setup of the calculation ($t\bar{t}\gamma\gamma$)

- Exclusive in $n_b = 2$
- Anti-k_T jet algorithm ($R = 0.4$) *Cacciari, Salam, Soyez '08*
- Event selection:

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

- 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 $\alpha_s = 0.118$ *Ball et. al. '17*

Setup of the calculation ($t\bar{t}\gamma\gamma$)

- 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 $\epsilon_\gamma = n = 1$

Integrated Fiducial cross section

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

- NLO QCD corrections ~30%
- Scale uncertainties reduced from 31% to 6%
- Only ~39% of Full from Prod.