NATIONAL CENTRE FOR SCIENTIFIC RESEARCH "DEMOKRITOS"
INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

H.F.R.I.
Hellenic Foundation for Research & Innovation

State of the art predictions for on-/off-shell top-pair production and decays

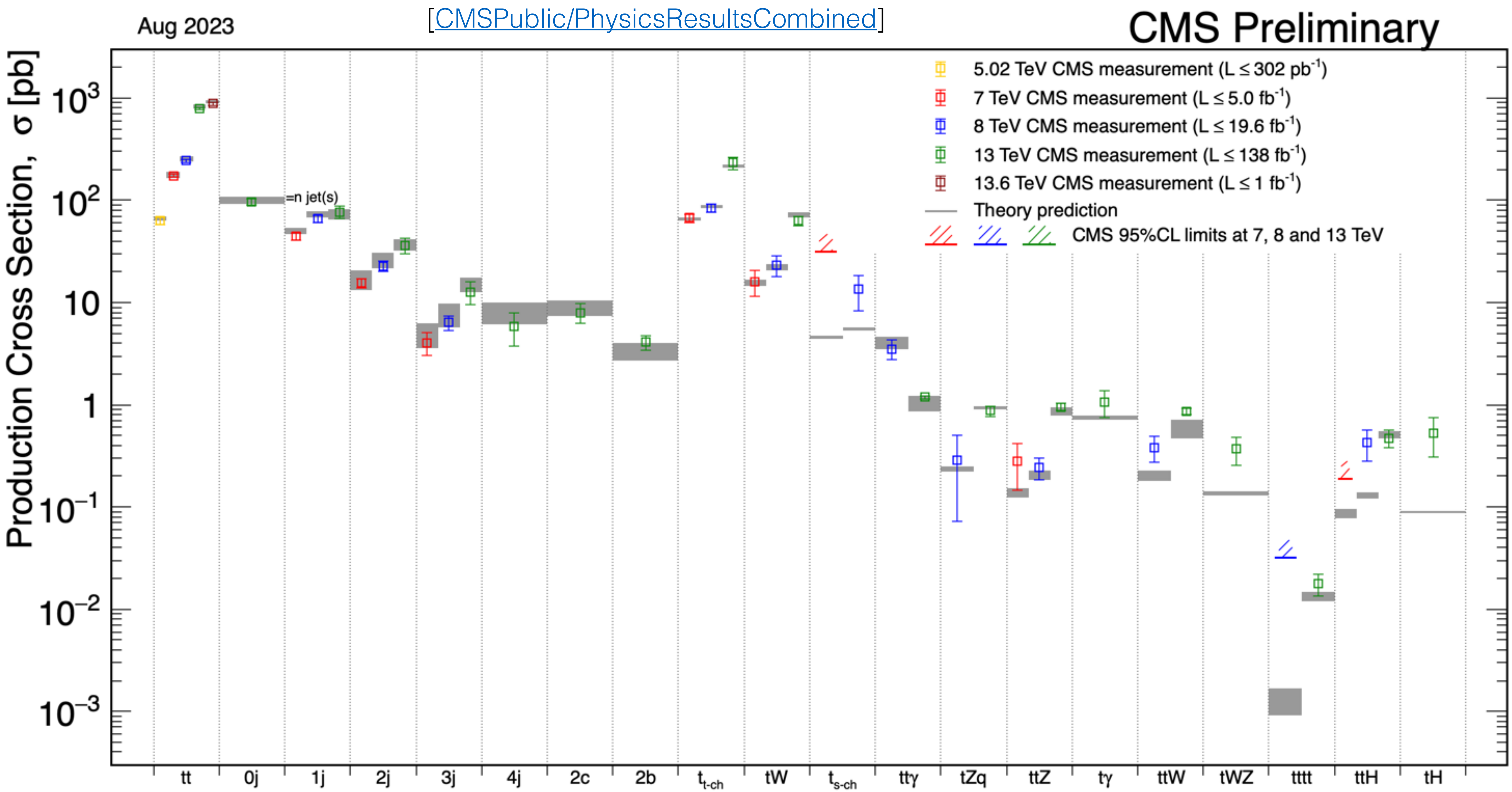
Giuseppe Bevilacqua
NCSR "Demokritos"

Standard Model at the LHC 2024

Rome, 10 May 2024

$t\bar{t}$ and associated production channels at the LHC

[CMSPublic/PhysicsResultsCombined]



$t\bar{t}$: theoretical status

- $t\bar{t}$ cross section @ LHC

NNLO (+ NNLL)

[Czakon, Fiedler, Mitov '13; Czakon, Heymes, Mitov '16 '17; Czakon, Heymes, Mitov, Pagani, Tsinikos '17; Czakon, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, Yang '18; Catani, Devoto, Grazzini, Kallweit, Mazzitelli '19 '20; Kidonakis, Guzzi, Tonero '23]

NNLO Prod × Decay

[Behring, Czakon, Mitov, Papanastasiou, Poncelet '19; Czakon, Mitov, Poncelet '21]

NNLO Prod × LO Decay ⊕ PS

[Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi '20 '21]

NLO off-shell

[G.B, Czakon, Van Hameren, Papadopoulos, Worek '11; Denner, Dittmaier, Kallweit, Pozzorini '11,'12; Cascioli, Kallweit, Maierhöfer, Pozzorini '14 Denner, Pellen '18]

NLO off-shell ⊕ PS

[Jezo, Lindert, Nason, Oleari, Pozzorini '16; Jezo, Lindert, Pozzorini '23]

Theoretical uncertainties (13 TeV)

NNLO QCD : ~ 5-6%

aN3LO QCD+EW : ~ 3%

[Phys.Rev.D 108 (2023) 5, 054012]

Recent progress in associated $t\bar{t} + X$ modelling

- First NNLO results $\rightarrow t\bar{t}H, t\bar{t}W$

  Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini '23
  Buonocore, Devoto, Grazzini, Kallweit, Mazzitelli, Rottoli, Savoini '23

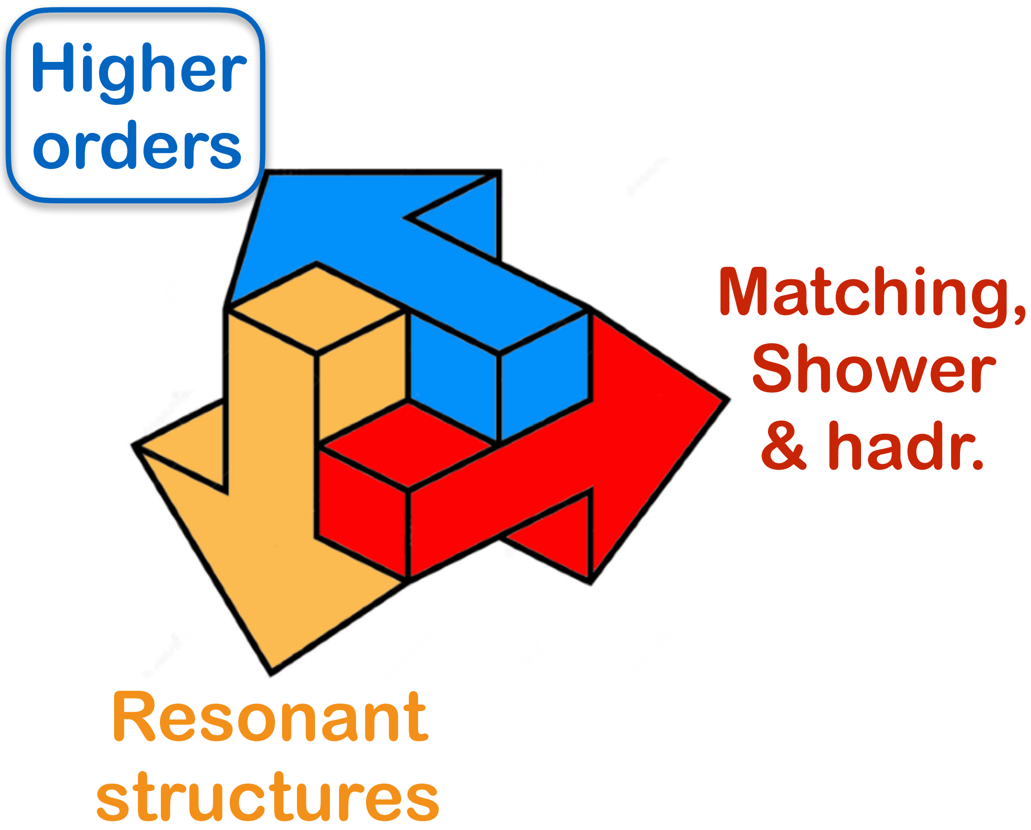
See also talks by A. Kulesza and M. Grazzini

- NNLL resummation $\rightarrow t\bar{t}H, t\bar{t}Z, t\bar{t}W, t\bar{t}t\bar{t}$

  [Kulesza, van Beekveld, Motyka, Stebel, Theeuwes, Moreno Valero; Broggio, Ferroglia, Frederix, Pagani, Pecjak, Tsinikos, Yang] '17-'22

- Complete NLO $\rightarrow t\bar{t}\gamma, t\bar{t}\gamma\gamma, t\bar{t}W, t\bar{t}Z \ldots$

  Denner, Pelliccioli '21
  Pagani, Shao, Tsinikos, Zaro '21
  Denner, Lombardi, Pelliccioli '23
  Stremmer, Worek '24



↪ • Precise predictions for inclusive production rates

• Impact of subleading perturbative contributions at integrated and differential level

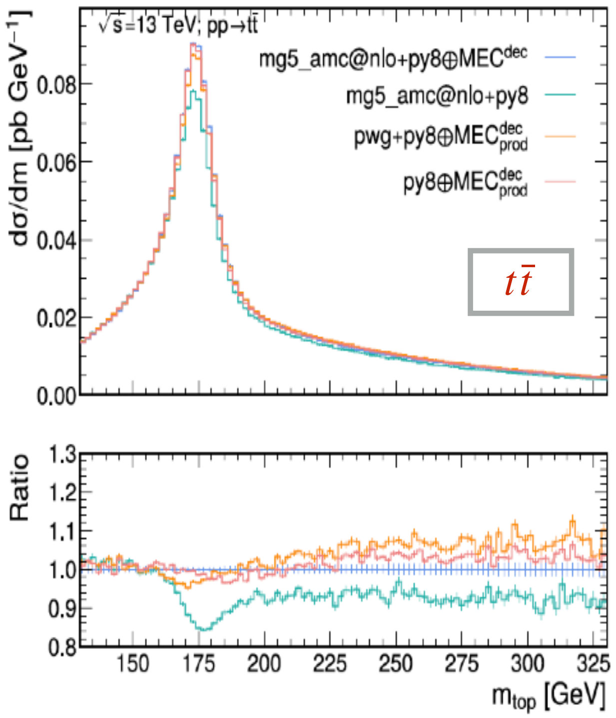
Recent progress in associated $t\bar{t} + X$ modelling

- Matrix element corrections (MEC) to top decays in MC@NLO based simulations

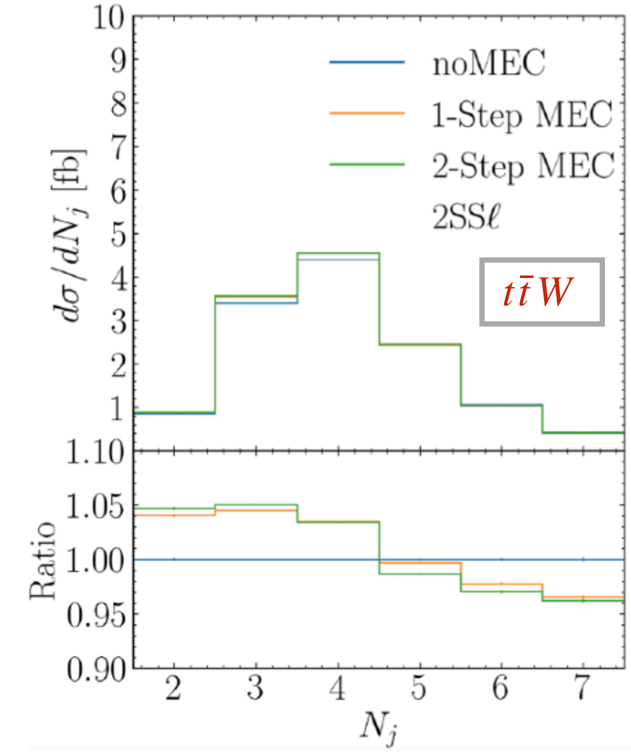
  Frixione, Amoroso, Mrenna '23
  Frederix, Gellersent, Nasufi '24

  ↪ • Improving hard-recoil effects in radiation off top-quarks

[Eur.Phys.J.C 83 (2023) 10, 970]



[Eur.Phys.J.C 84 (2024) 4, 410]

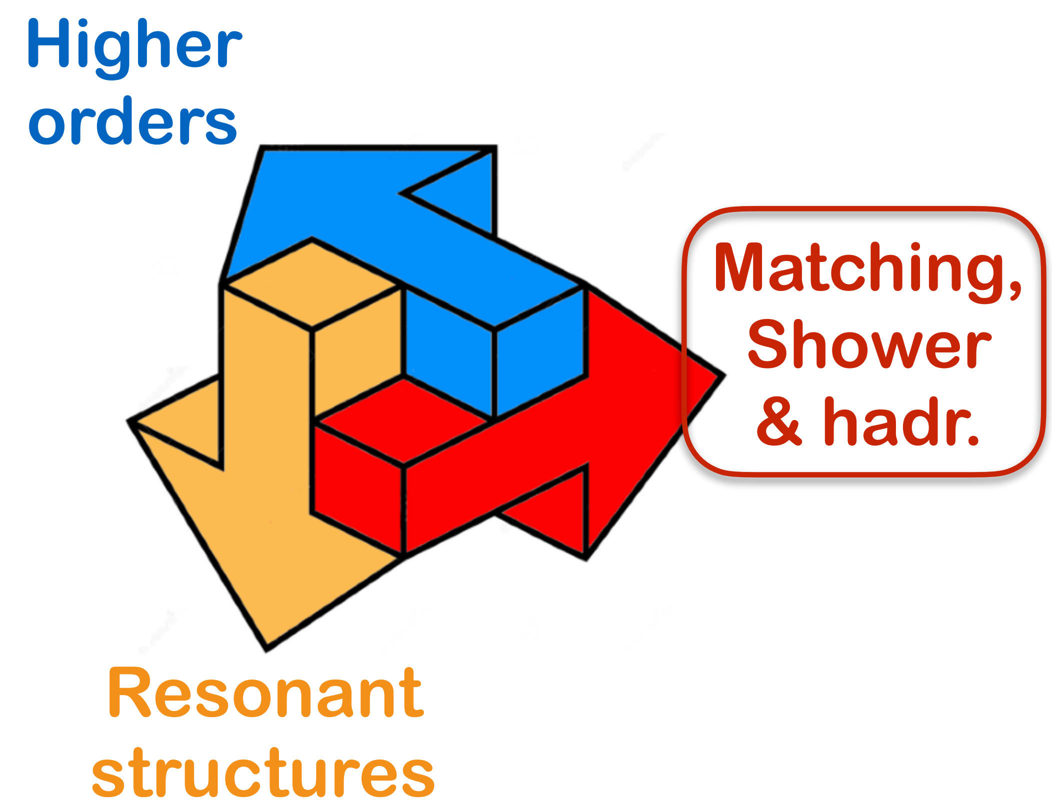


- Improved resonance-aware matching for off-shell $t\bar{t} + tW$ simulations (POWHEG)

  Jezo, Lindert, Pozzorini '23

  ↪ • Improving description of single-resonant contributions

  • Extending bb4l generator to semi-leptonic channel



Recent progress in associated $t\bar{t}+X$ modelling

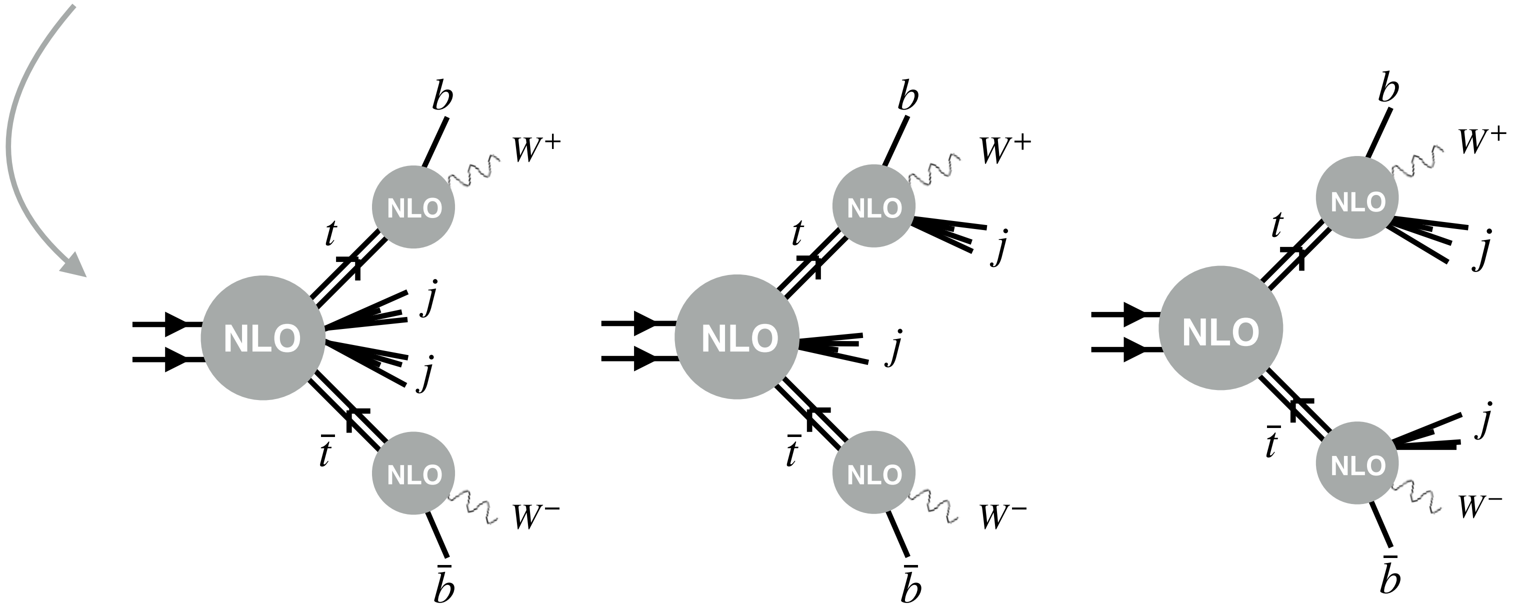
Fixed-order NLO

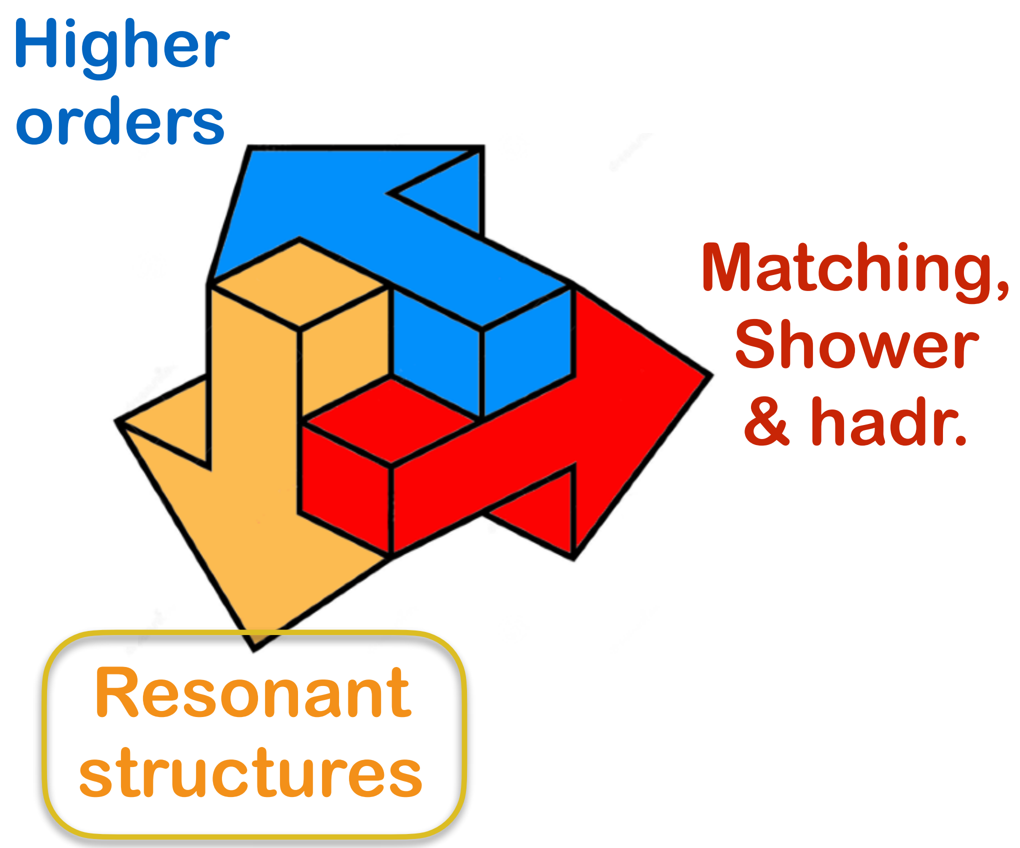
- *Off-shell* **studies** $\rightarrow$ $t\bar{t}X \; (X = \gamma, j, W, Wj, Z, H, b\bar{b})$

  [G.B., Hartanto, Kraus, Worek '15-'16] [G.B., Hartanto, Kraus, Weber, Worek '18-'20] [G.B., Bi, Hartanto, Kraus, Nasufi, Worek '20-'21] [G.B., Bi, Febres Cordero, Hartanto, Kraus, Nasufi, Reina, Worek '22] [G.B., Bi, Hartanto, Kraus, Lupattelli, Worek '21-'23] [Hermann, Worek '21] [Hermann, Stremmer, Worek '22] [Bi, Kraus, Reinartz, Worek '23]
  [Denner, Pellen '17] [Denner, Lang, Pellen, Uccirati '17] [Denner, Pelliccioli '20-'21] [Denner, Lang, Pellen '21] [Denner, Lombardi, Pelliccioli '23]

- *On-shell* **studies (full NWA)** $\rightarrow$ $t\bar{t}jj, t\bar{t}\gamma\gamma, t\bar{t}t\bar{t}$

  G.B., Lupattelli, Stremmer, Worek '23
  Stremmer, Worek '23
  Dimitrakopoulos, Worek '24





Recent progress in associated $t\bar{t} + X$ modelling

Fixed-order NLO

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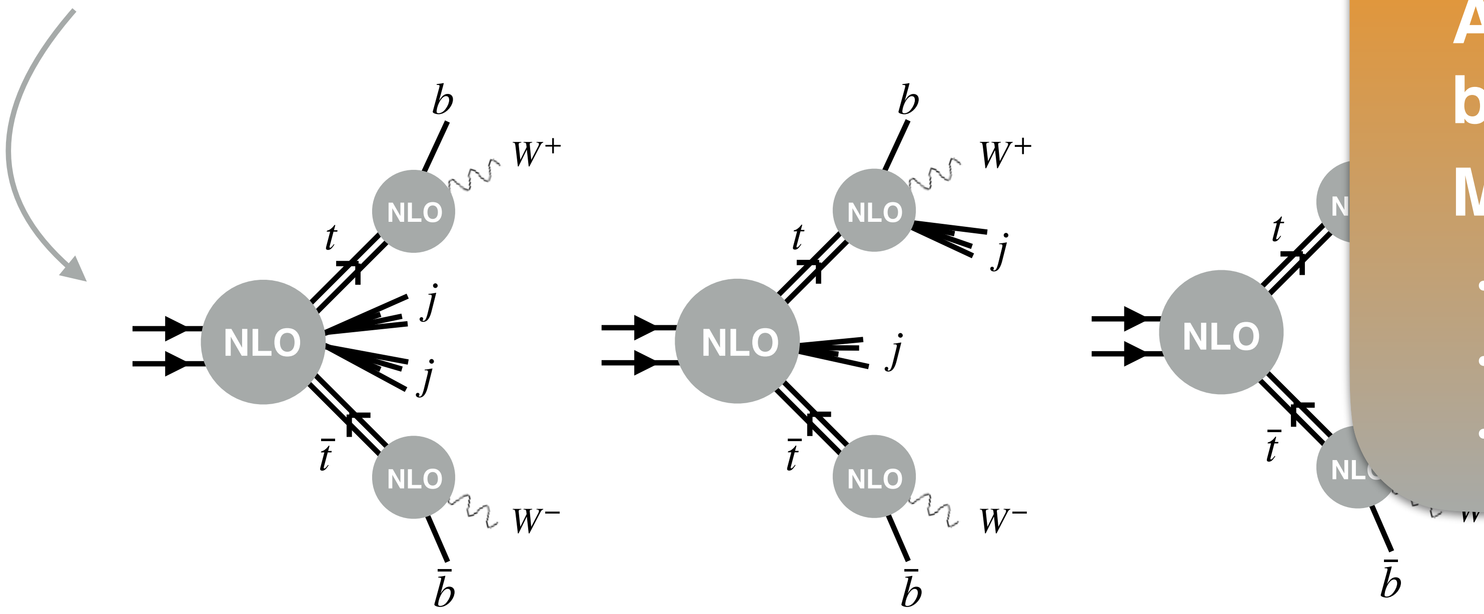


Disclaimer

A limited selection of results will be discussed in the following.

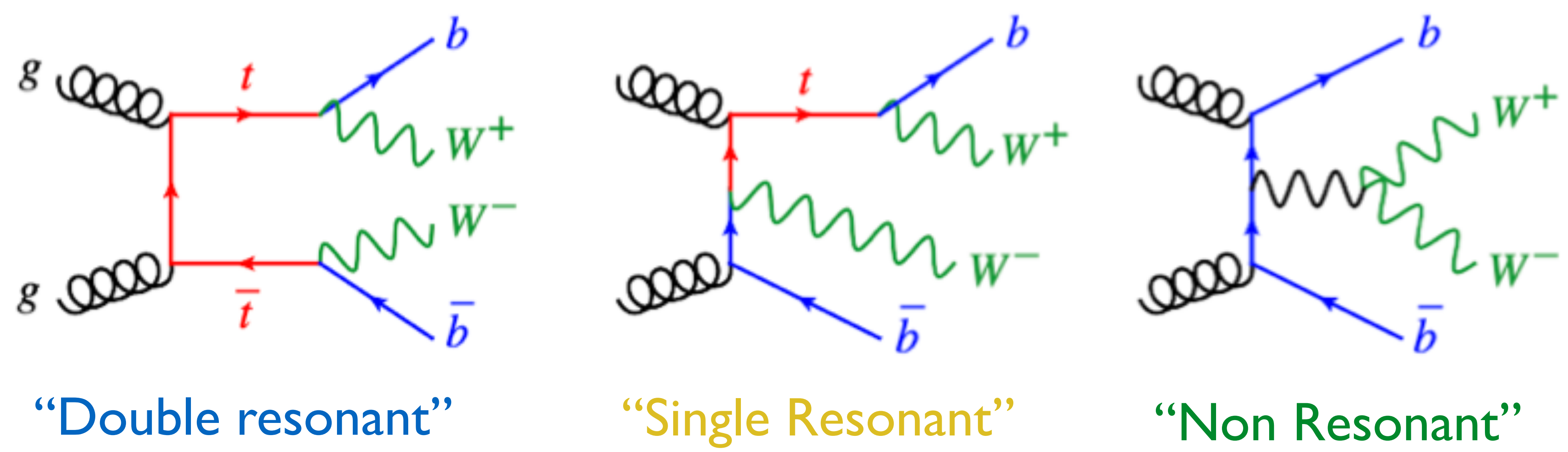
Main focus:

- **Impact of full off-shell effects**
- **Complete NLO corrections**
- **Modelling of resonant structures**

Offshell in a nutshell

- Simplest example: $pp \to b\bar{b}W^+W^-$

"Off-shell"



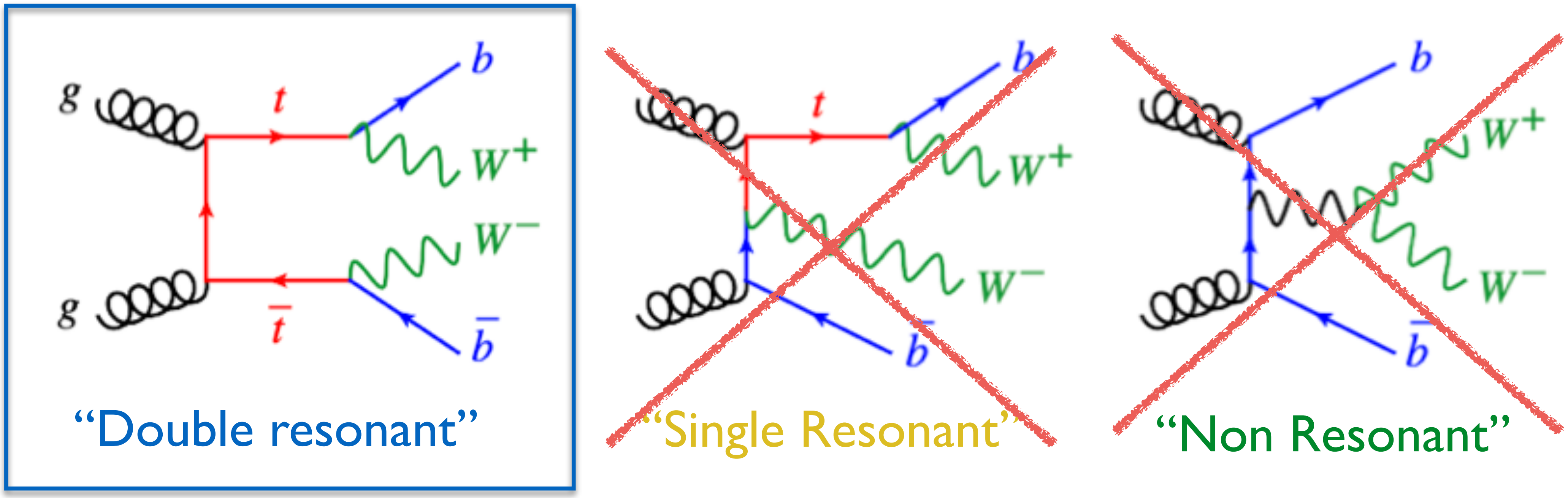
"Off-shell" = DR + SR + NR + interferences

Narrow Width Approximation

$\Gamma_t/m_t \approx 0.008$ $\Gamma_W/m_W \approx 0.026$

- Simplest example: $pp \to b\bar{b}W^+W^-$ $\to$ NWA

"Off-shell"



" $t\bar{t}$ "

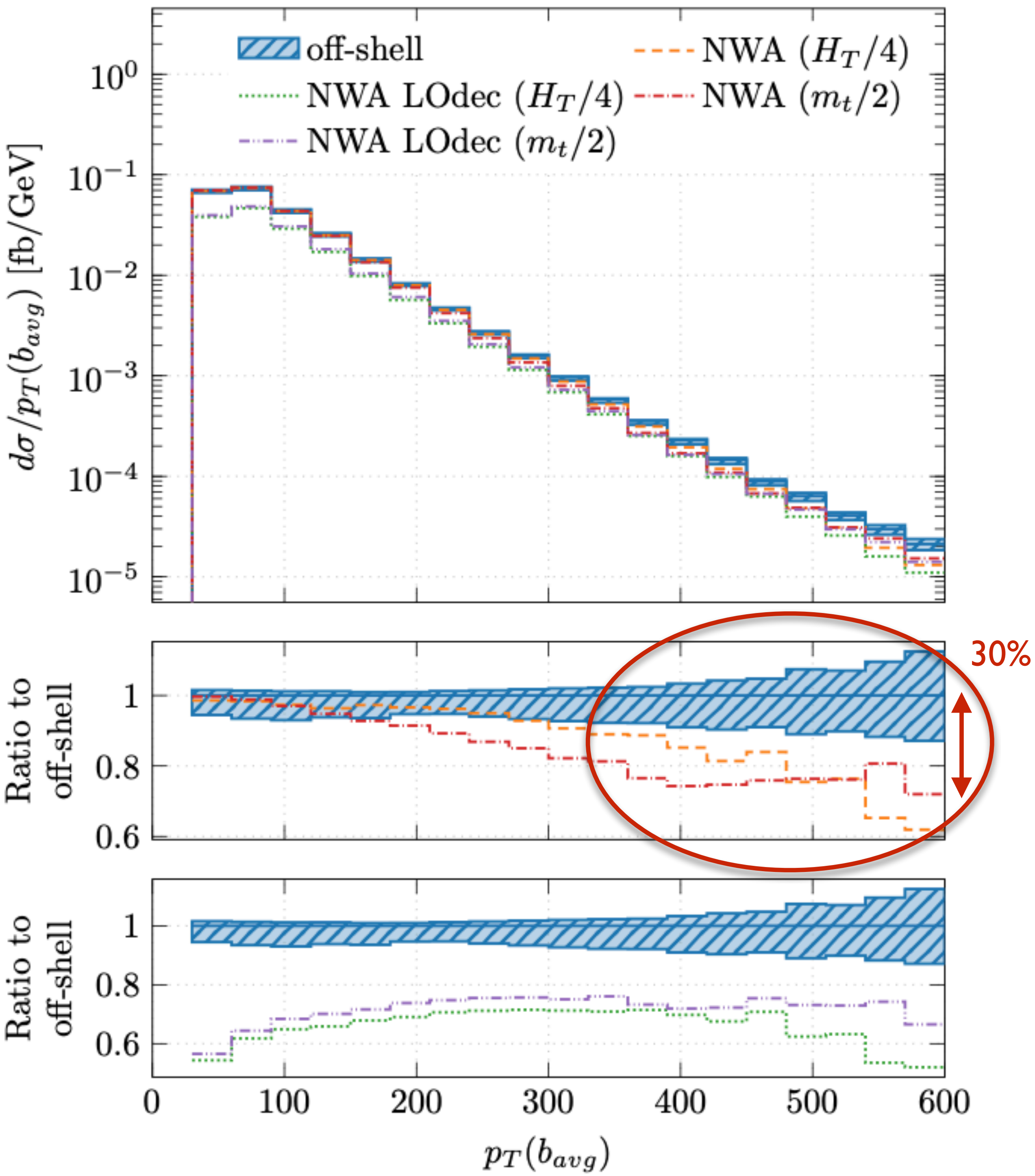
$\Gamma_t/m_t \to 0$ $\Rightarrow$

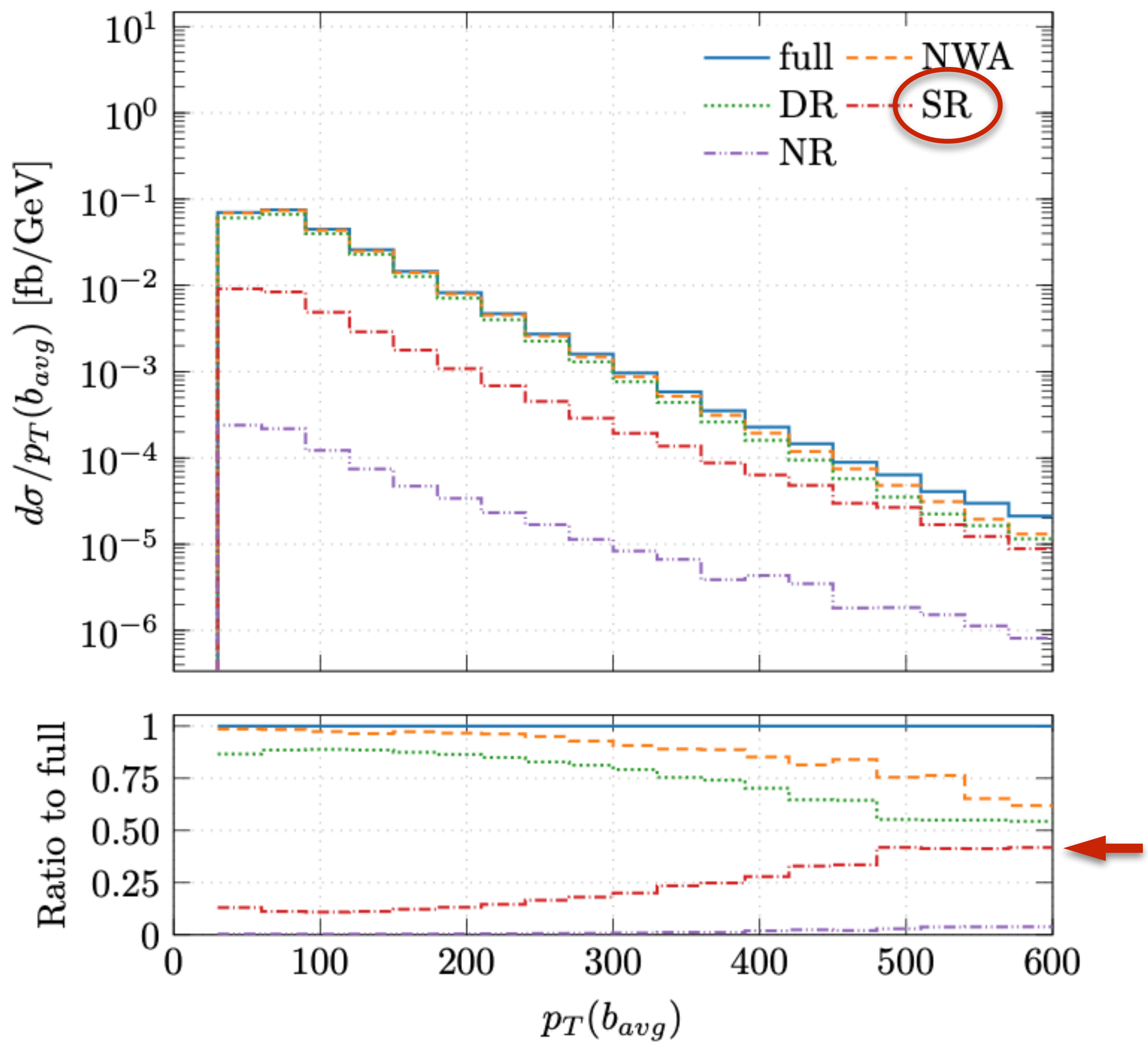
$$\frac{1}{(p_t^2-m_t^2)^2+m_t^2\Gamma_t^2} \overset{\Gamma_t \to 0}{\sim} \frac{\pi}{m_t\Gamma_t}\,\delta(p_t^2-m^2)+\mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)$$

Off-shell effects are suppressed by powers of $\Gamma_t/m_t = \mathcal{O}(1\%)$ for *sufficiently inclusive* observables $\to$ not always true differentially

Off-shell effects

$pp \to t\bar{t}\gamma$ (dilepton)



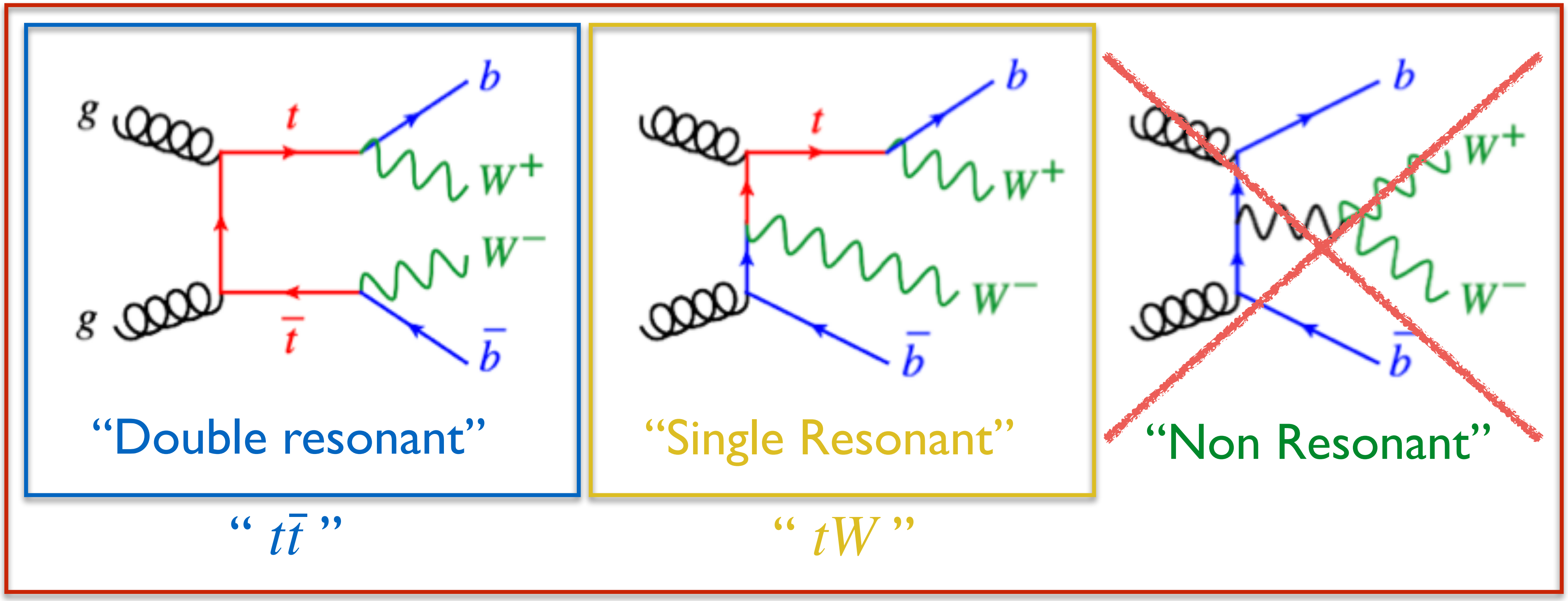


GB, Hartanto, Kraus, Weber and Worek

JHEP 03 (2020) 154

- Simplest example: $pp \to b\bar{b}W^+W^-$ $\to$ NWA

"Off-shell"



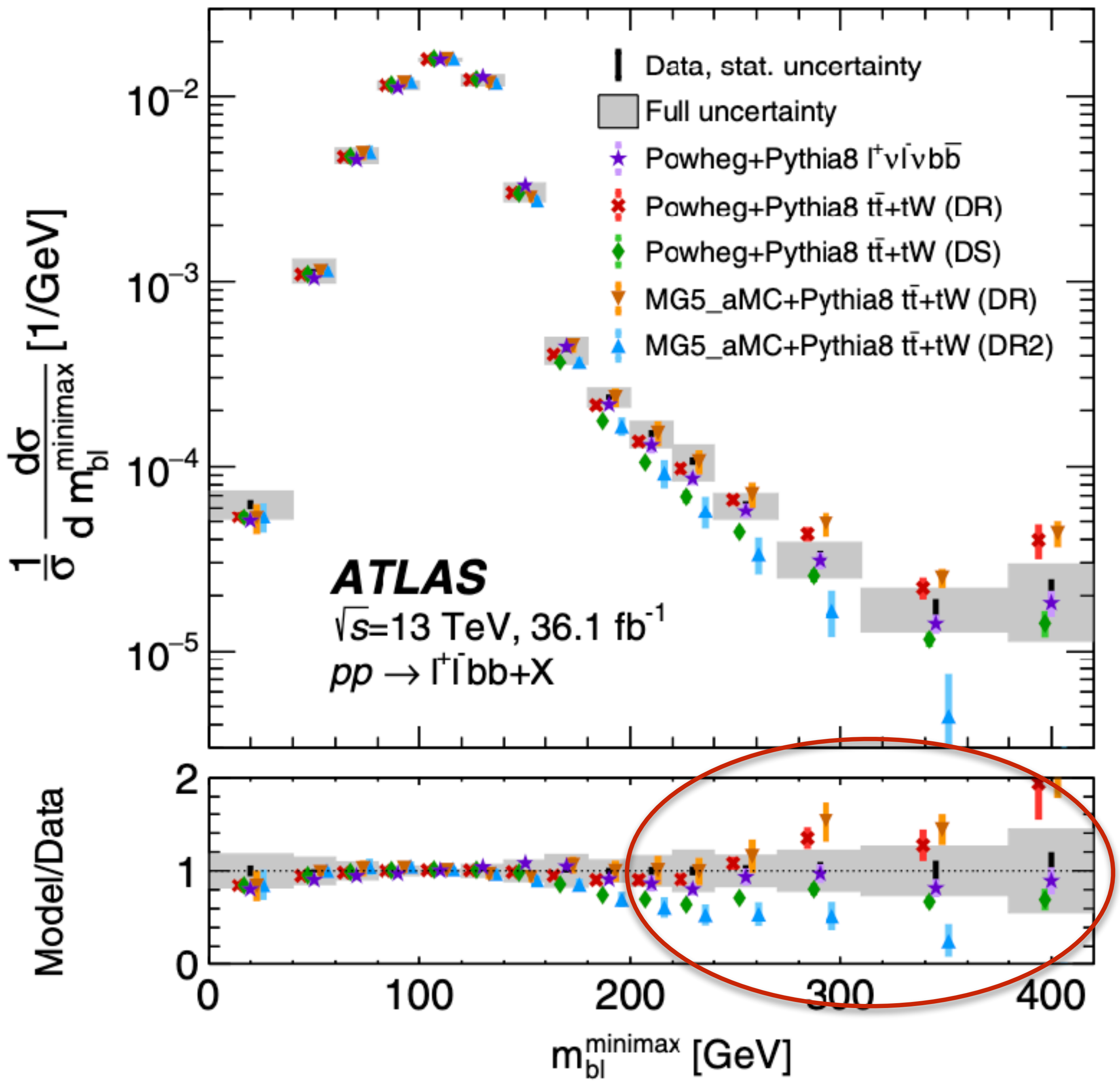
$\Gamma_t/m_t \to 0$

Overlapping $t\bar{t}/tW(b)$

$\hookrightarrow$ Diagram Subtraction (DS) $\leftrightarrow$ Diagram Removal (DR)

$t\bar{t} - tW$ interference effects

[ATLAS Collab., Phys. Rev. Lett. 121 (2018)]



- Semi-leptonic channel
  $pp \to \ell^+ \nu_\ell \ell^- \bar{\nu}_\ell b\bar{b}$

- Full off-shell vs $t\bar{t} + tW(b)$ at NLO+PS

- Full off-shell models well all regions

- $t\bar{t} + tW(b)\,|_{DR,DS}$ differ numerically
  ↪ systematic comparisons

Model	All bins	$m_{b\ell}^{\text{minimax}} > 160$ GeV
POWHEG-BOX $t\bar{t} + tW$ (DR)	0.71	0.40
POWHEG-BOX $t\bar{t} + tW$ (DS)	0.77	0.56
MG5_aMC $t\bar{t} + tW$ (DR)	0.14	0.17
MG5_aMC $t\bar{t} + tW$ (DR2)	0.02	0.08
POWHEG-BOX $\ell^+\nu\ell^-\nu bb$	0.92	0.95

$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

Off-shell $t\bar{t}$ @ NLO QCD + PS

- Semi-leptonic channel
  $pp \to e^+\nu_e\, jj\, b\bar{b}$

[Jezo, Lindert and Pozzorini, JHEP10 (2023) 008]

	bb4l-sl	hvq+ST_{wtch}-DS	hvq+ST_{wtch}-DR
$t \to Wb$ and $W \to q\bar{q}'$ decays	NLO+PS	LO+PS	LO+PS
tWb production	NLO+PS	LO+PS	LO+PS
$t\bar{t}$-tW interference	NLO+PS	—	LO+PS
off-shell effects	NLO+PS	approx.	approx.
non-resonant contributions	NLO+PS	—	—

Comparison against on-shell $t\bar{t} + tW$ generators → integrated level

		inclusive phase space		$e^+\nu_e bbjj$ fiducial phase space			
				$R=0.5$		$R=0.2$	
		σ[pb]	$\frac{\sigma}{\sigma^{\mathrm{NLOPS}}_{\mathrm{bb4l-sl}}}$	σ[pb]	$\frac{\sigma}{\sigma^{\mathrm{NLOPS}}_{\mathrm{bb4l-sl}}}$	σ[pb]	$\frac{\sigma}{\sigma^{\mathrm{NLOPS}}_{\mathrm{bb4l-sl}}}$
bb4l-sl	NLOPS	57.56(2)	1	16.30(1)	1	14.639(9)	1
bb4l-sl	LHE	57.56(2)	1	16.33(1)	1.002	17.17(1)	1.173
hvq	NLOPS	54.340(9)	0.944	15.910(6)	0.976	14.244(6)	0.973
ST_{wtch}-DS	NLOPS	2.5194(3)	0.044	0.4877(2)	0.030	0.4232(2)	0.029
ST_{wtch}-DR	NLOPS	2.5524(3)	0.044	0.5249(2)	0.032	0.4683(2)	0.032
hvq + ST_{wtch}-DS	NLOPS	56.859(8)	0.988	16.398(6)	1.006	14.667(6)	1.002
hvq + ST_{wtch}-DR	NLOPS	56.892(8)	0.988	16.475(6)	1.011	14.780(6)	1.010

- Impact of tW contribution: $\sim 5\,\%$

Off-shell $t\bar{t}$ @ NLO QCD + PS

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- Impact of tW contribution: $\sim 5\,\%$
- Small $t\bar{t}$ - tW interference

Off-shell $t\bar{t}$ @ NLO QCD + PS

- **Semi-leptonic channel**
  $pp \to e^+\nu_e\, jj\, b\bar{b}$

[Jezo, Lindert and Pozzorini, JHEP10 (2023) 008]

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$t\bar{t}$-tW interference	NLO+PS	—	LO+PS
off-shell effects	NLO+PS	approx.	approx.
non-resonant contributions	NLO+PS	—	—

Comparison against on-shell $t\bar{t} + tW$ generators → integrated level

		inclusive phase space		$e^+\nu_e bbjj$ fiducial phase space			
				$R=0.5$		$R=0.2$	
		σ[pb]	$\frac{\sigma}{\sigma^{NLOPS}_{bb4l-sl}}$	σ[pb]	$\frac{\sigma}{\sigma^{NLOPS}_{bb4l-sl}}$	σ[pb]	$\frac{\sigma}{\sigma^{NLOPS}_{bb4l-sl}}$
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hvq + ST_{wtch}-DR	NLOPS	56.892(8)	0.988	16.475(6)	1.011	14.780(6)	1.010

- Impact of tW contribution: $\sim 5\,\%$
- Small $t\bar{t}$ - tW interference
- $t\bar{t} + tW$ accurate at $\sim 1\,\%$
  ↪ using MEC

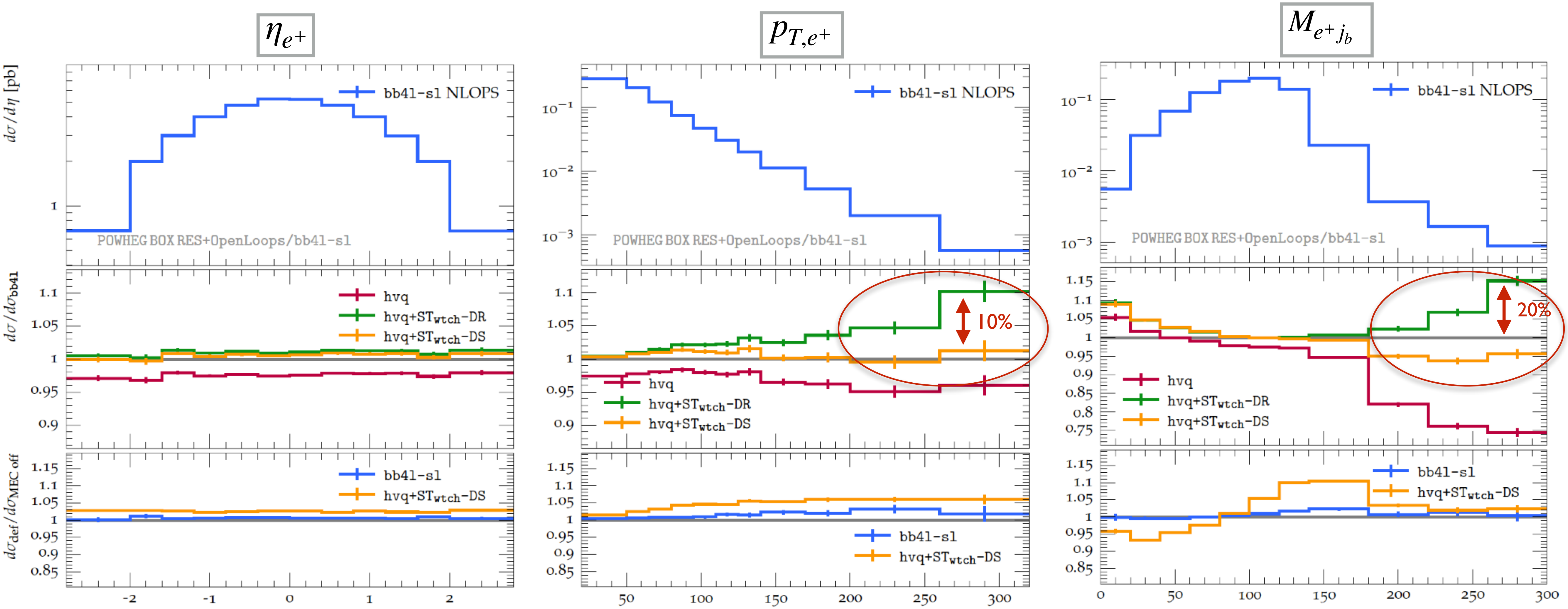
Off-shell $t\bar{t}$ @ NLO QCD + PS

- **Semi-leptonic channel**

  $pp \to e^+ \nu_e \, jj \, b\bar{b}$

[Jezo, Lindert and Pozzorini, JHEP10 (2023) 008]

Comparison against on-shell $t\bar{t} + tW$ generators → differential level

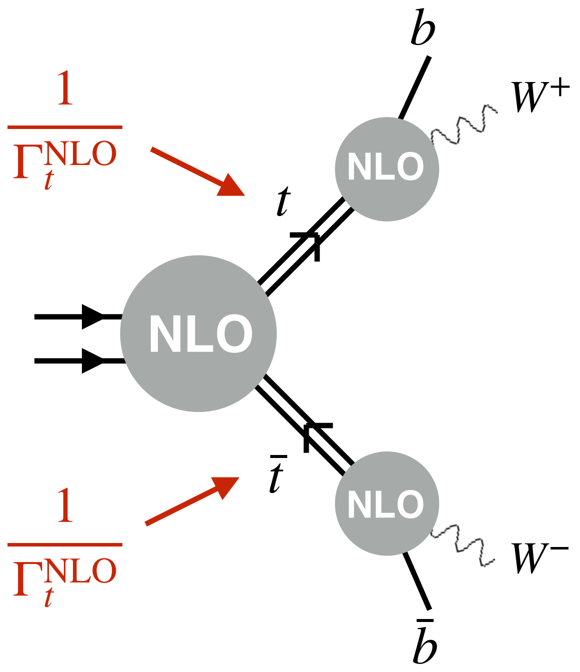


Off-shell $t\bar{t}$ @ NLO QCD + PS

[Jezo, Lindert and Pozzorini, JHEP10 (2023) 008]

- **Inverse-width expansion**

↪ removes "spurious" terms $\mathcal{O}(\alpha_s)$



- $\mathcal{O}(\alpha_s)$ effects numerically larger than tW:

↪ $$\left.\frac{\sigma_{\mathtt{bb4l-sl}}}{\sigma_{\mathtt{hvq+ST}}}\right|_{\text{no } 1/\Gamma_t \text{ expansion}} = 1.074$$

$$d\sigma^{\mathrm{NLO_{exp}}}_{\mathrm{NWA}} = \left(\prod_{r\in\mathcal{R}} \frac{\Gamma_{r,\mathrm{NLO}}}{\Gamma_{r,0}}\right)\left[d\sigma^{\mathrm{NLO}}_{\mathrm{NWA}} - \left(\sum_{r\in\mathcal{R}} \frac{\Gamma_{r,1}}{\Gamma_{r,0}}\right) d\sigma^{(0)}_{\mathrm{NWA}}\right]$$

$$d\sigma^{\mathrm{NLO_{exp}}}_{\mathrm{off-shell}} \equiv \left(\prod_{r\in\mathcal{R}} \frac{\Gamma_{r,\mathrm{NLO}}}{\Gamma_{r,0}}\right)\left[d\sigma^{\mathrm{NLO}}_{\mathrm{off-shell}} - \left(\sum_{r\in\mathcal{R}} \frac{\Gamma_{r,1}}{\Gamma_{r,0}}\right) d\sigma^{(0)}_{\mathrm{off-shell}}\right]$$

Off-shell $t\bar{t}b\bar{b}$ @ NLO QCD

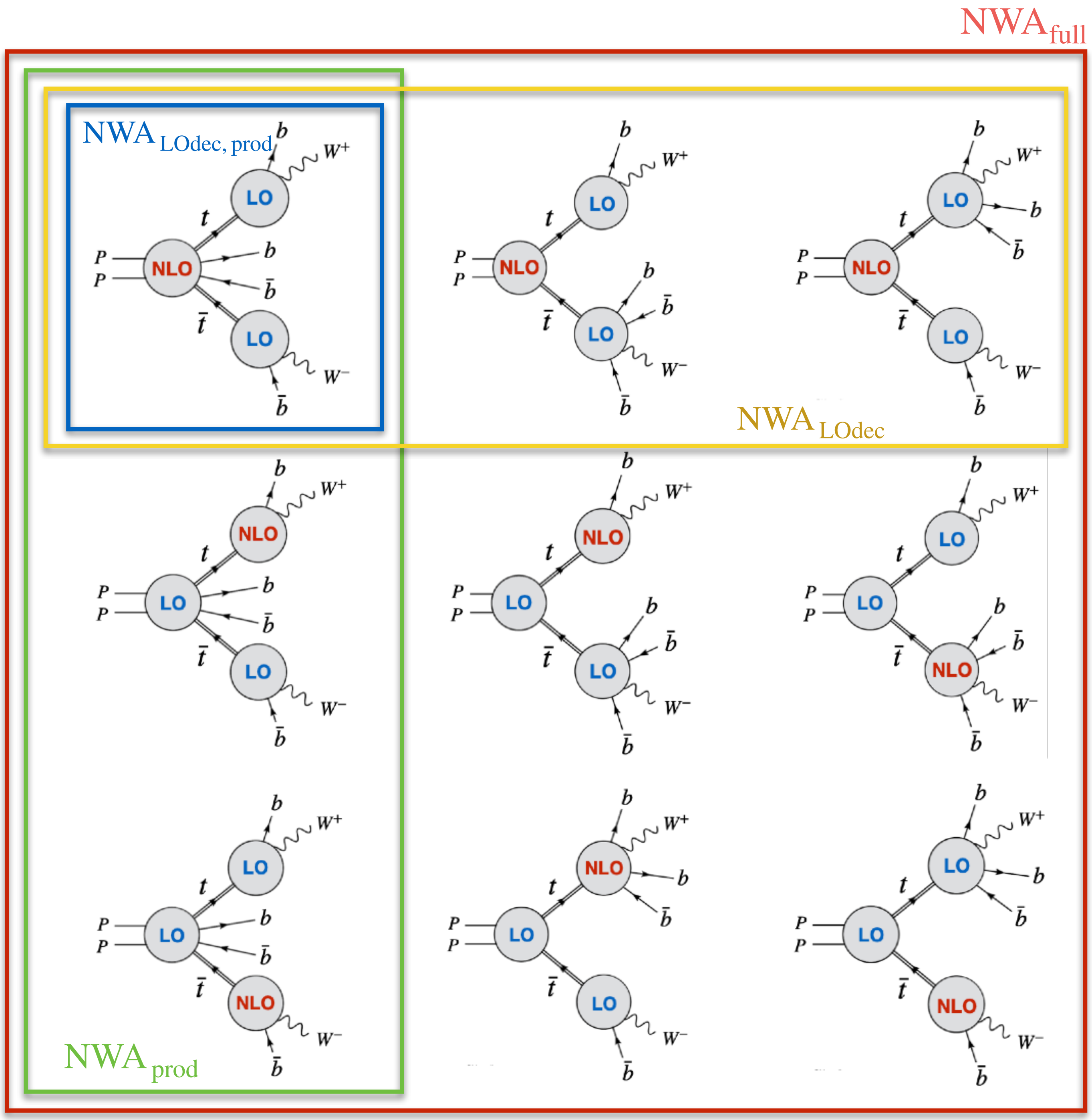
- **Di-lepton channel** [GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

  $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$

Full off-shell vs NWA (double res.)

Modelling	σ^{NLO} [fb]	δ_{scale} [fb]	$\frac{\sigma^{\mathrm{NLO}}}{\sigma^{\mathrm{NLO}}_{\mathrm{NWA_{full}}}} - 1$
Off-shell	13.22(2)	$^{+2.65\ (20\%)}_{-2.96\ (22\%)}$	+0.5%
$\mathrm{NWA_{full}}$	13.16(1)	$^{+2.61\ (20\%)}_{-2.93\ (22\%)}$	–
$\mathrm{NWA_{LOdec}}$	13.22(1)	$^{+3.77\ (29\%)}_{-3.31\ (25\%)}$	+0.5%
$\mathrm{NWA_{prod}}$	13.01(1)	$^{+2.58\ (20\%)}_{-2.89\ (22\%)}$	−1.1%
$\mathrm{NWA_{prod,\,exp}}$	12.25(1)	$^{+2.87\ (23\%)}_{-2.86\ (23\%)}$	−6.9%
$\mathrm{NWA_{prod,\,LOdec}}$	13.11(1)	$^{+3.74\ (29\%)}_{-3.28\ (25\%)}$	−0.4%

NWA predictions based on different accuracies in top decay modelling



Off-shell $t\bar{t}b\bar{b}$ @ NLO QCD

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Full off-shell vs NWA (double res.)

Modelling	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$ [fb]	$\frac{\sigma^{\rm NLO}}{\sigma^{\rm NLO}_{\rm NWA_{full}}} - 1$
Off-shell	13.22(2)	$^{+2.65\ (20\%)}_{-2.96\ (22\%)}$	+0.5%
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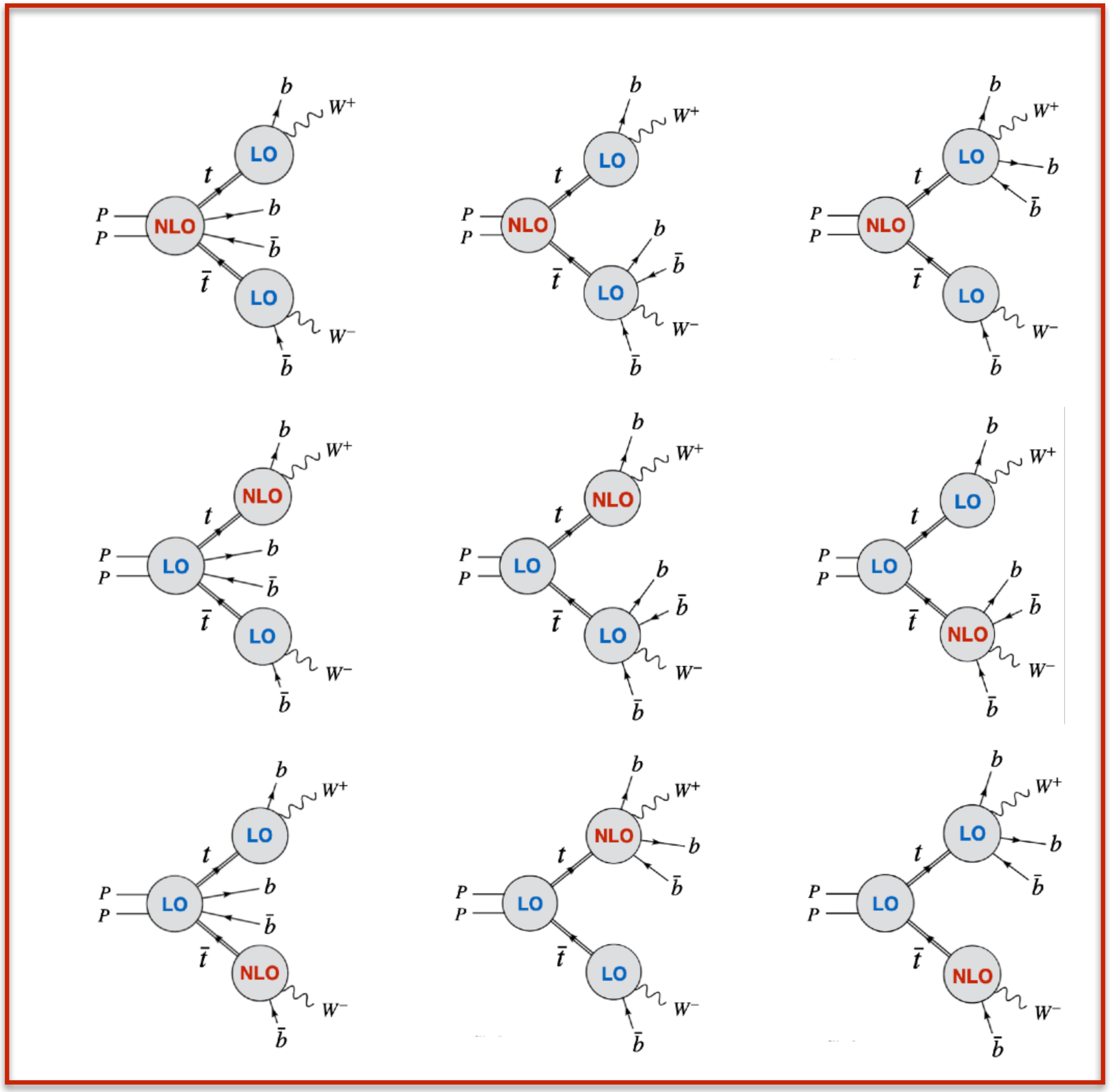
$\rm NWA_{full}$



- Genuine off-shell effects:

  +0.5 %

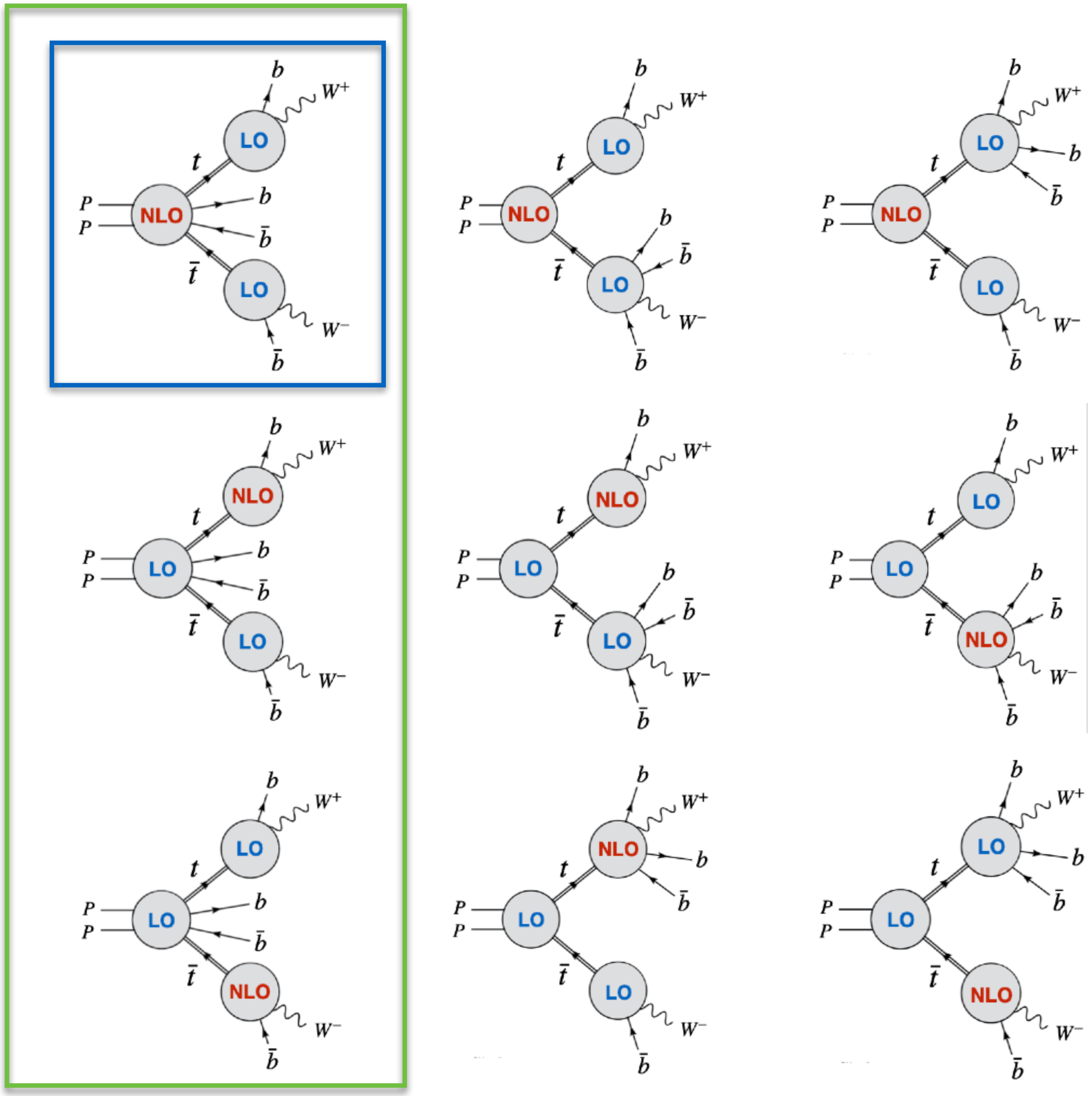
Off-shell $t\bar{t}b\bar{b}$ @ NLO QCD

- **Di-lepton channel**
  $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

Full off-shell vs NWA (double res.)

Modelling	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$ [fb]	$\frac{\sigma^{\rm NLO}}{\sigma^{\rm NLO}_{{\rm NWA}_{\rm full}}} - 1$
Off-shell	13.22(2)	$^{+2.65\ (20\%)}_{-2.96\ (22\%)}$	+0.5%
$\rm NWA_{full}$	13.16(1)	$^{+2.61\ (20\%)}_{-2.93\ (22\%)}$	–
$\rm NWA_{LOdec}$	13.22(1)	$^{+3.77\ (29\%)}_{-3.31\ (25\%)}$	+0.5%
$\rm NWA_{prod}$	13.01(1)	$^{+2.58\ (20\%)}_{-2.89\ (22\%)}$	−1.1%
$\rm NWA_{prod,\,exp}$	12.25(1)	$^{+2.87\ (23\%)}_{-2.86\ (23\%)}$	−6.9%
$\rm NWA_{prod,\,LOdec}$	13.11(1)	$^{+3.74\ (29\%)}_{-3.28\ (25\%)}$	−0.4%



- Impact of QCD corrections to decays: $-7\,\%$

Off-shell $t\bar{t}b\bar{b}$ @ NLO QCD

- **Di-lepton channel**

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

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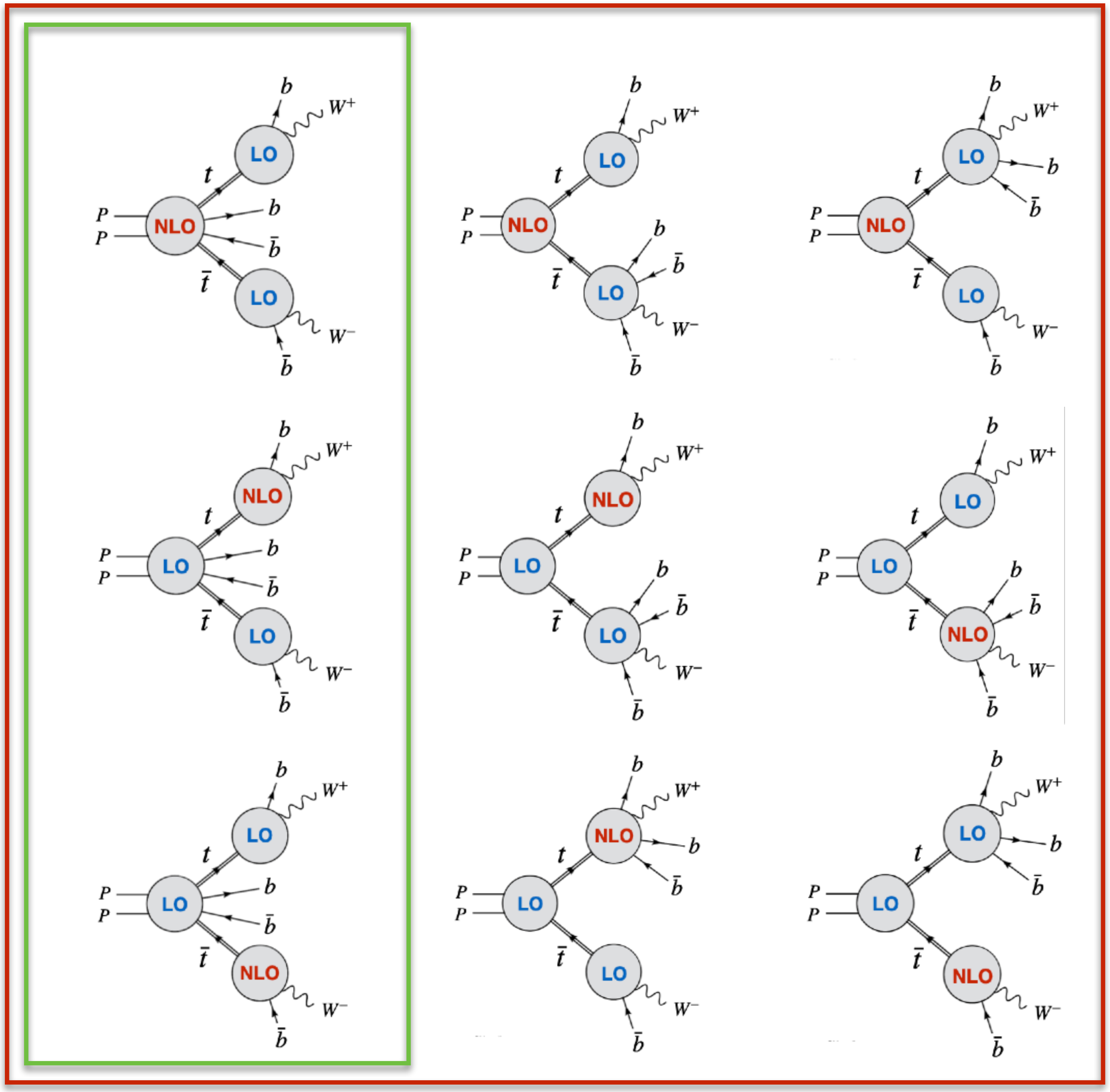
- Impact of $t \to Wbb\bar{b}$ decays:

  $+1\,\%$

$\rm NWA_{full}$



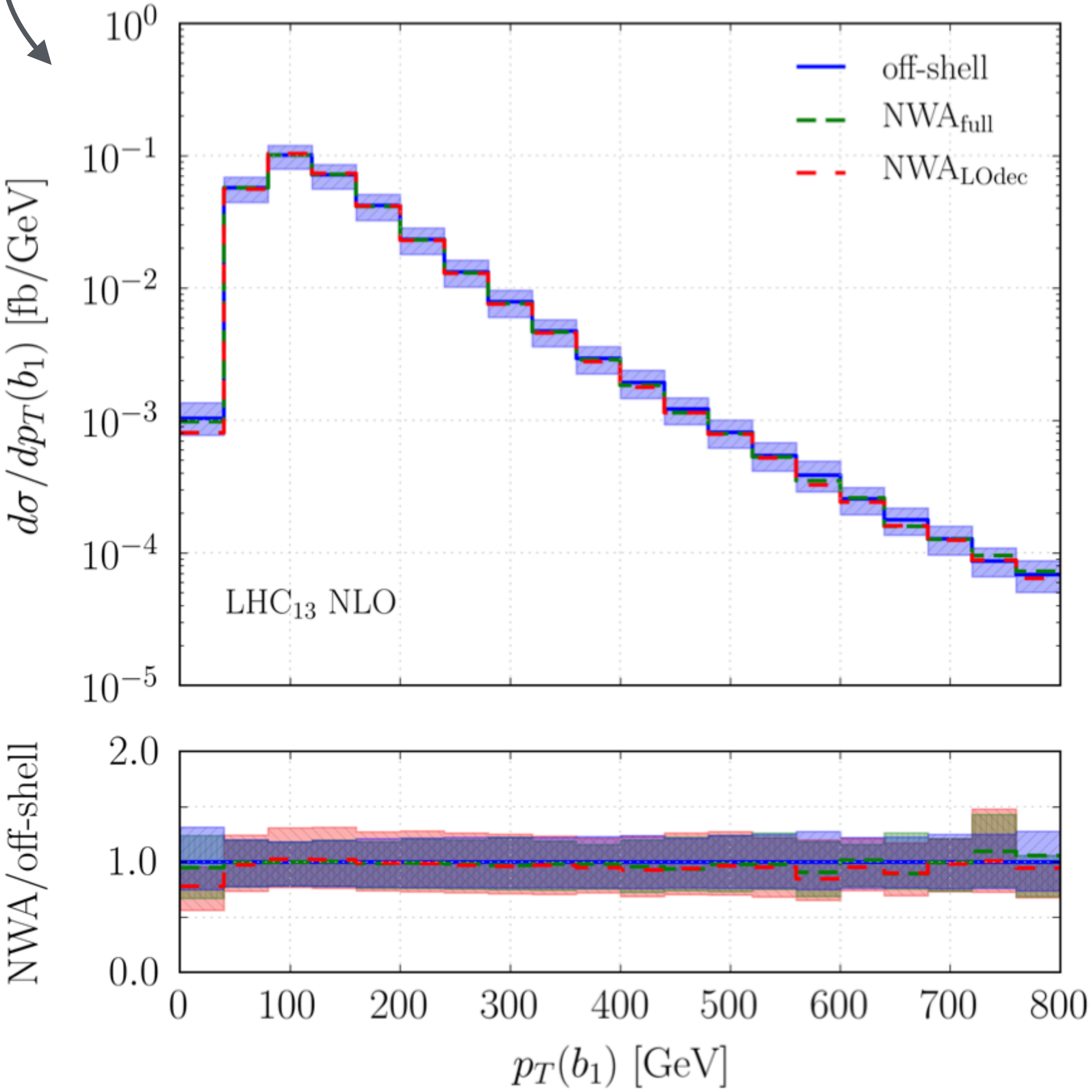
Off-shell $t\bar{t}b\bar{b}$ @ NLO QCD

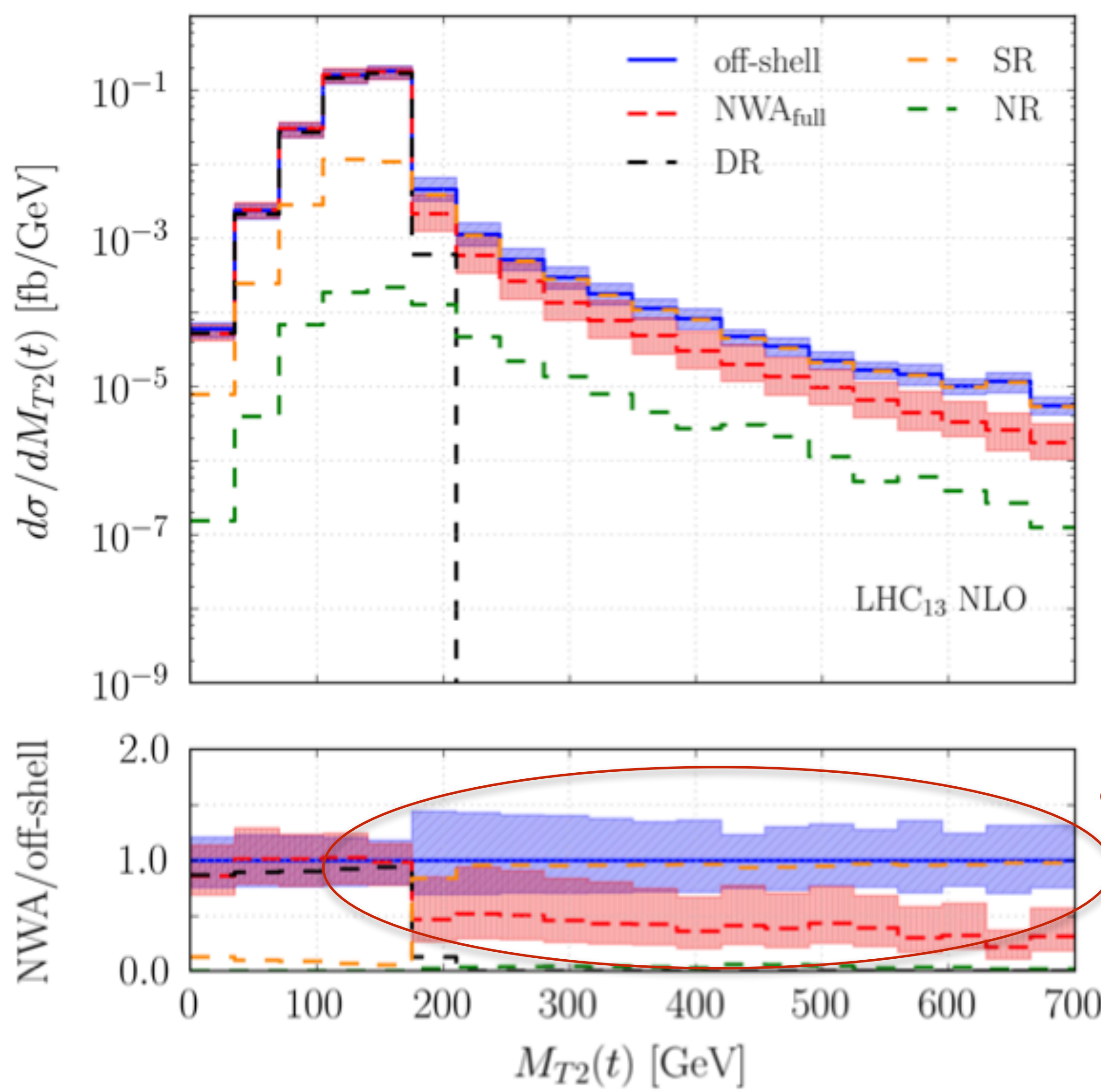
- **Di-lepton channel** [GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

  $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$

Off-shell effects at sub-percent level for most observables used for precision SM studies

Threshold observables (interesting for searches) are naturally more sensitive





$$M_{T2}(t) = \min_{\sum_i p_T^{\nu_i} = p_t^{miss}} \left[\max\{ M_T\left(p_T(e^+ X_t), p_T(\nu_1)\right), M_T\left(p_T(\mu^- X_{\bar{t}}), p_T(\nu_2)\right)\} \right]$$

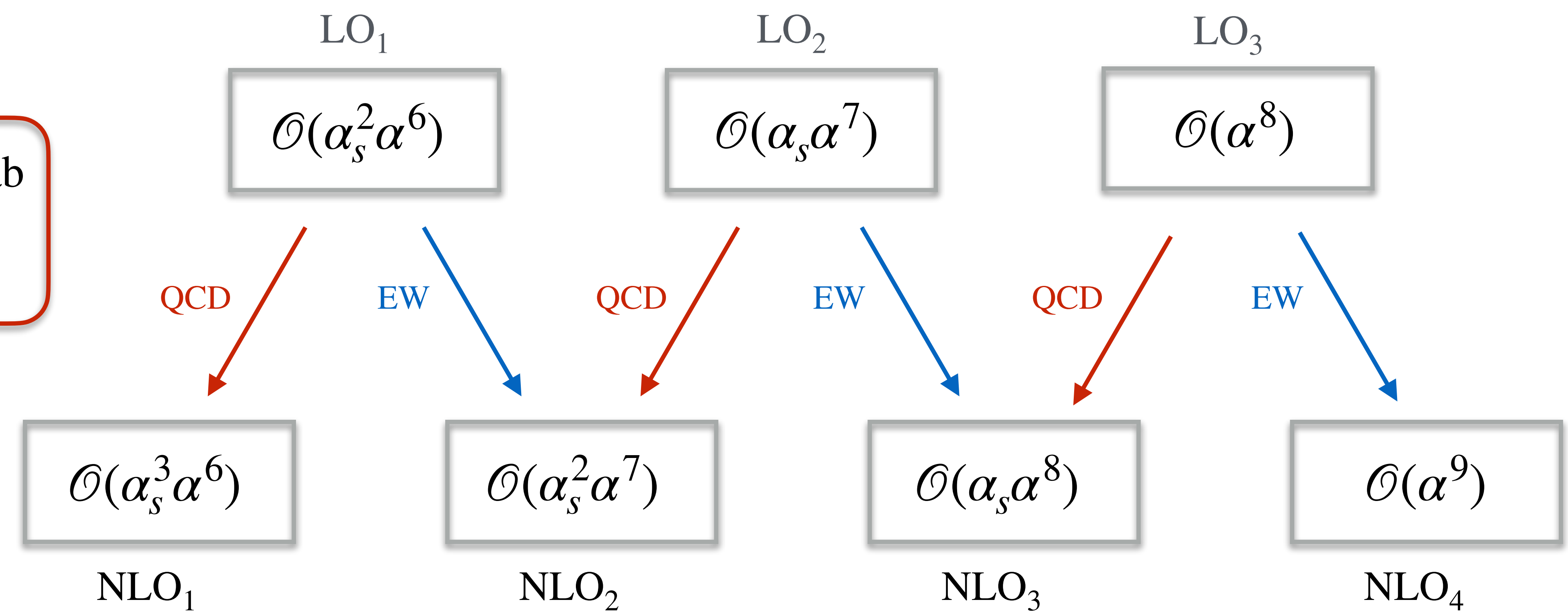
Off-shell $t\bar{t}Z$ @ complete NLO

- **Multi-lepton channel**
  $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu\tau^+\tau^-b\bar{b}$

[Denner, Lombardi and Pellicciolli, JHEP09 (2023) 072]

$$\sigma_{\rm LO} = 108.756(5)^{+34.5\%}_{-23.7\%}\ \text{ab}$$

$$\sigma_{\rm NLO} = 98.0(1)^{+0.4\%}_{-10.6\%}\ \text{ab}$$



Ratio to LO_1 →	$-10.2\,\%$	$-0.7\,\%$	$+1\,\%$	$-0.05\,\%$

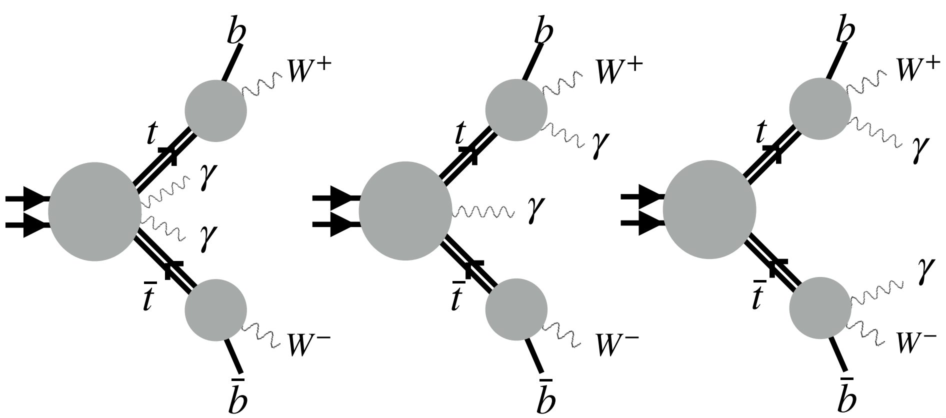
- Subleading effects ($\text{NLO}_{2,3,4}$) of the order of 1% at integrated level
- NLO_2 impacts up to -10% differentially → EW Sudakov logs at work

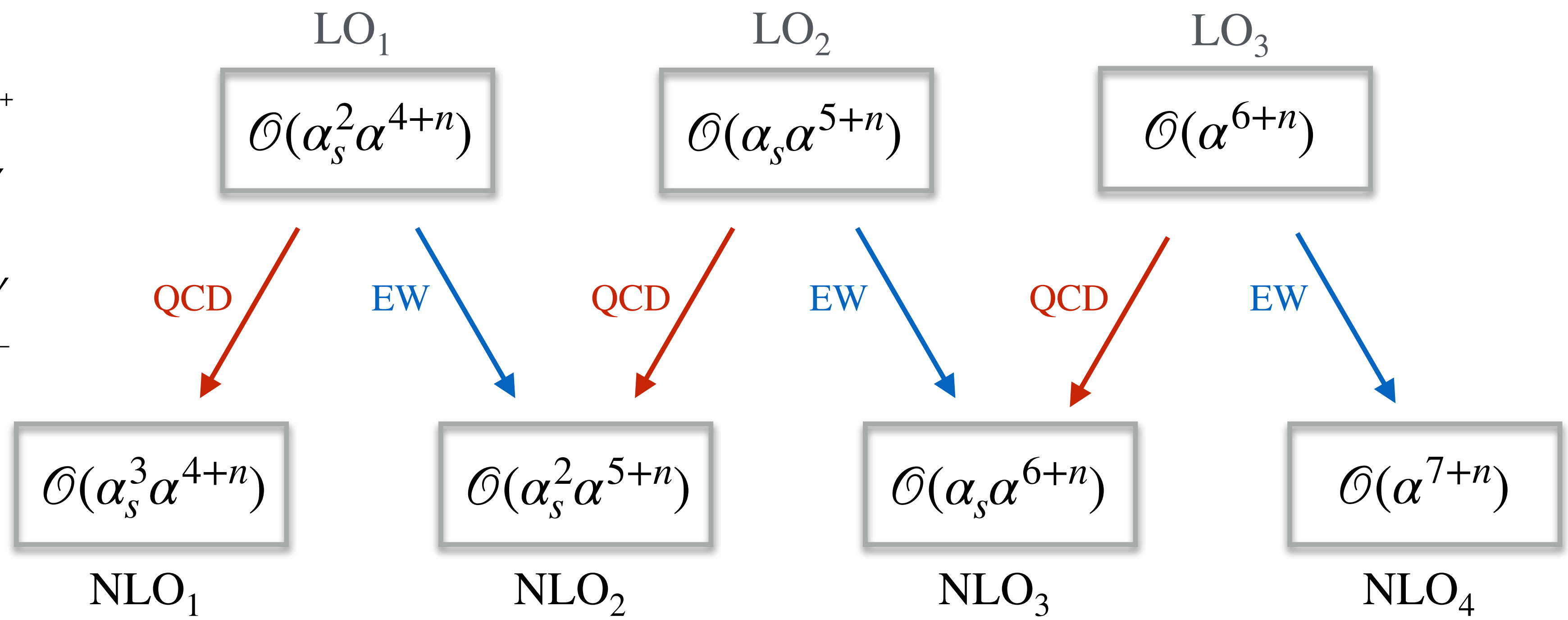
See also talks by S. Schumann and A. Kulesza

- Di-lepton channel
  $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma(\gamma)$

Full NWA

[Stremmer and Worek, arXiv:2403.03796 [hep-ph]]





Ratio to LO_1 :	NLO_1	NLO_2	NLO_3	NLO_4
$pp \to t\bar{t}\gamma$	$+6.2\,\%$	$-0.3\,\%$	$+0.4\,\%$	$+0.003\,\%$
$pp \to t\bar{t}\gamma\gamma$	$+6.9\,\%$	$-1.5\,\%$	$+0.4\,\%$	$-0.01\,\%$

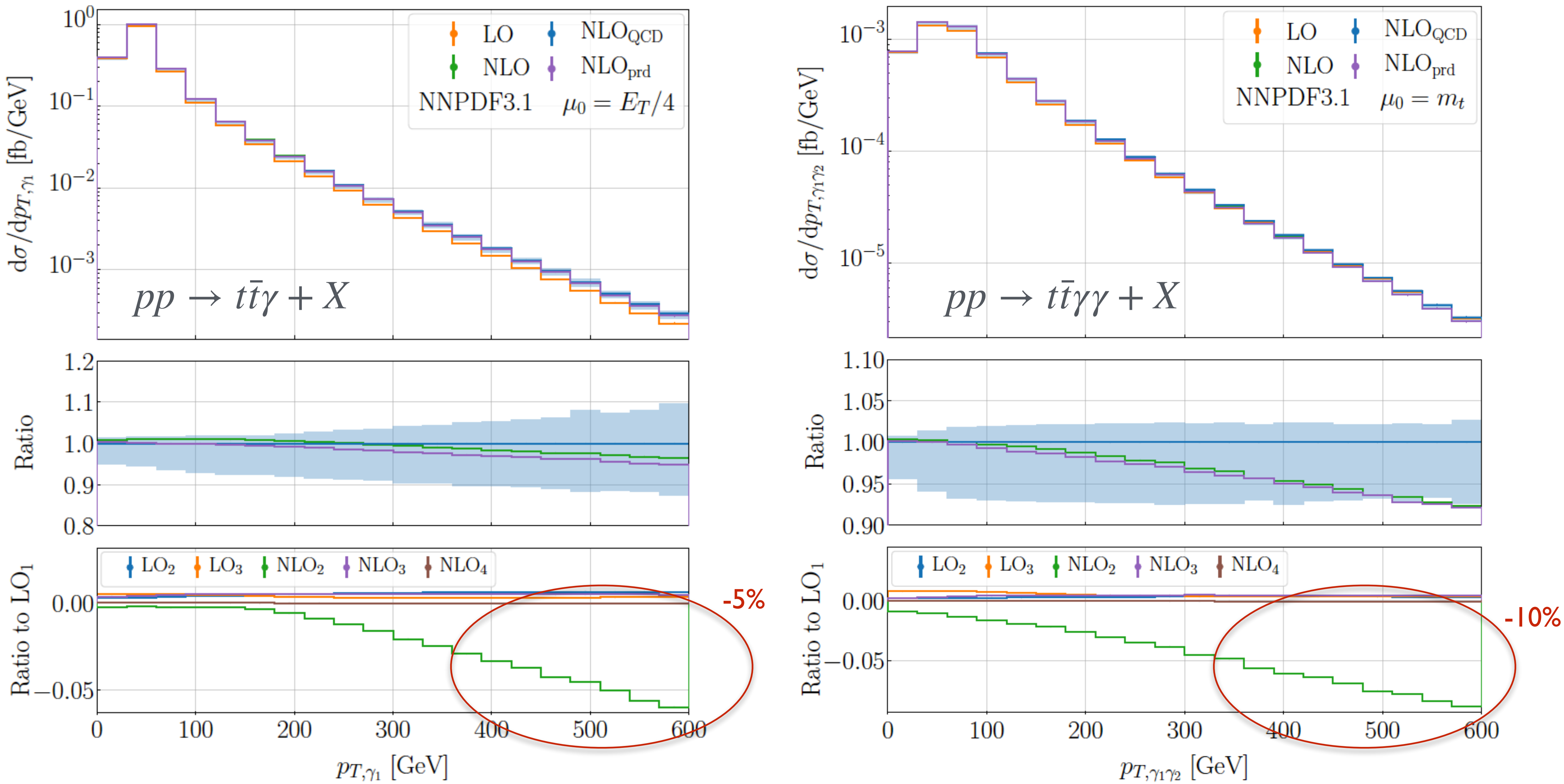
- Dominant NLO_1 correction essential for precise predictions
  ↪ residual scale uncertaities ~ 6%

- Subleading effects ($\mathrm{NLO}_{2,3,4}$) at the level of 1%

On-shell $t\bar{t} + n\,\gamma$ @ complete NLO

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma(\gamma)$ **Full NWA**

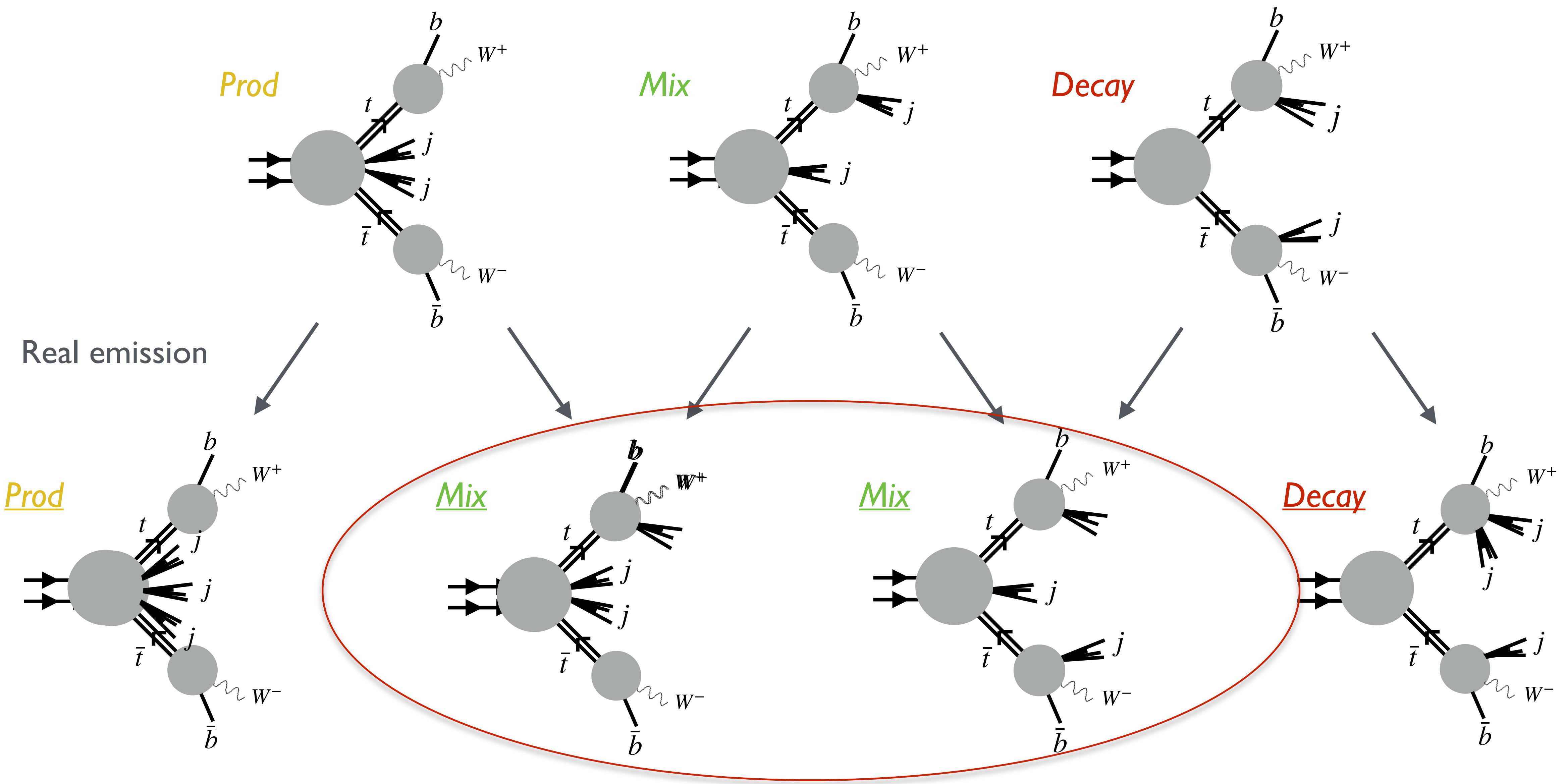
[Stremmer and Worek, arXiv:2403.03796 [hep-ph]]



- NLO$_2$ enhanced up to -10% in tails of dimensionful observables
- Neglecting γ brehmstralung and subleading corrections in decays ($\equiv$ NLO$_{prd}$) is accurate at 2%

On-shell $t\bar{t}jj$ @ NLO QCD

- What's the impact of different resonant contributions on fiducial cross section?



↪ $t\bar{t}j$ (7 TeV, semilept.) → $\sigma_{\rm NLO} = 323\,(\text{Prod}) - 75.5\,(\text{Mix}) + 40.5\,(\text{Dec}) = 288$ fb

-25% of $\sigma_{\rm NLO}$ [Melnikov, Scharf, Schulze '12]

On-shell $t\bar{t}jj$ @ NLO QCD

- **Di-lepton channel**
  $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}jj$

Full NWA

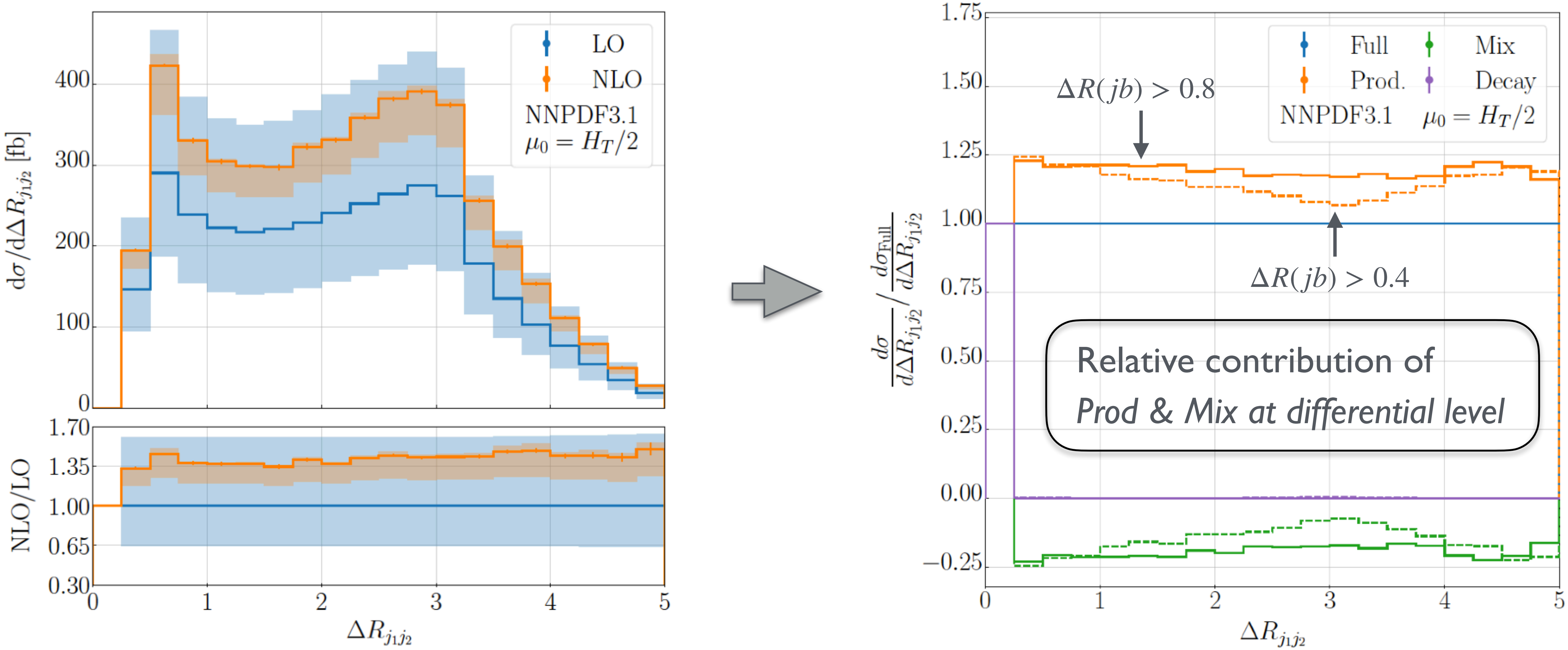
[GB, Lupattelli, Stremmer and Worek
Phys. Rev. D (107) 2023, 114027]

$\Delta R(jb) > 0.8 \quad \to \quad \sigma_{\rm NLO} = 1462\,(\text{Prod}) - 236\,(\text{Mix}) + 0.2\,(\text{Dec}) = 1225 \text{ fb}$

-19% of $\sigma_{\rm NLO}$

$\Delta R(jb) > 0.4 \quad \to \quad \sigma_{\rm NLO} = 1662\,(\text{Prod}) - 205\,(\text{Mix}) + 2.4\,(\text{Dec}) = 1460 \text{ fb}$

-14% of $\sigma_{\rm NLO}$



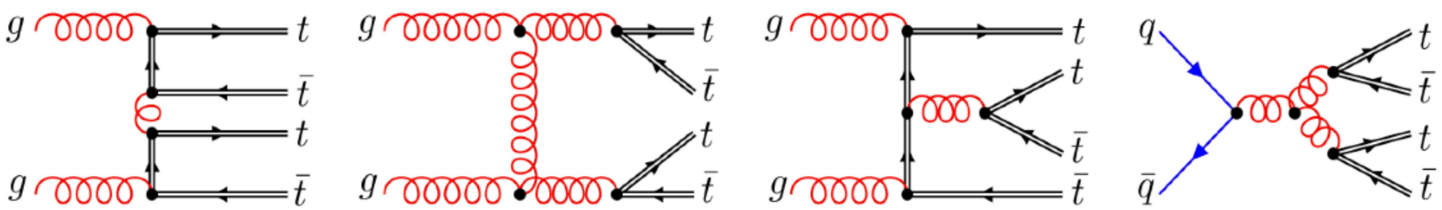
Relative contribution of
Prod & Mix at differential level

On-shell $t\bar{t}t\bar{t}$ @ NLO QCD

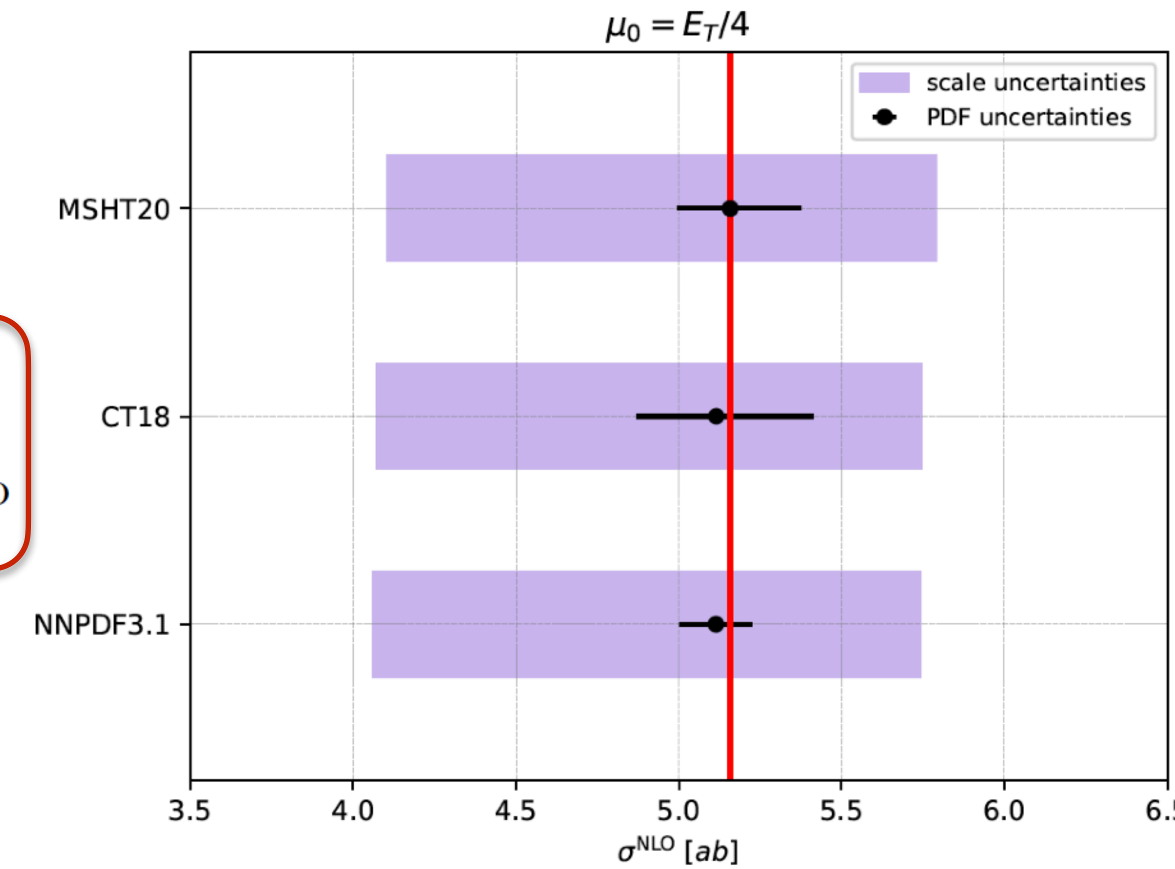
- 4ℓ **channel**

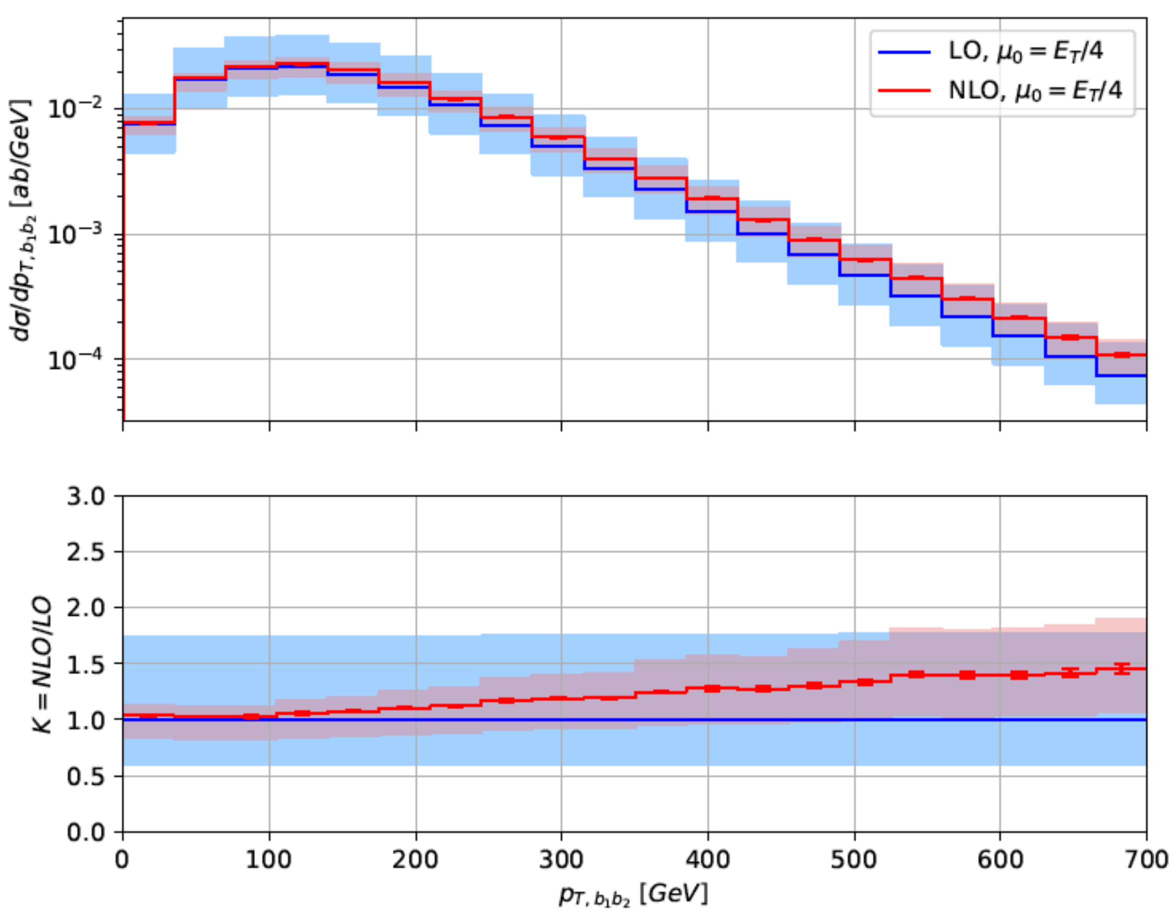
Full NWA

[Dimitrakopoulos and Worek, arXiv:2401.10678 [hep-ph]]



$$\sigma^{\rm LO}(\text{MSHT20}, \mu_0 = E_T/4) = 4.7479(3)^{+74\%}_{-40\%}\ [\text{scale}]\ \text{ab}\,,$$
$$\sigma^{\rm NLO}(\text{MSHT20}, \mu_0 = E_T/4) = 5.158(3)^{+12\%}_{-20\%}\ [\text{scale}]\ {}^{+4\%}_{-3\%}\ [\text{PDF}]\ \text{ab}$$





Residual scale uncertainties:

$\mathcal{O}(20\%)$

Impact of QCD corrections to decays:

$-8\,\%$

Summary

- Precision $t\bar{t} + X$ phenomenology sets a number of theoretical challenges
  - Perturbative accuracy
  - Decay modelling
  - PS matching & modelling
- Many interesting developments in recent times
  - Accurate predictions for inclusive $t\bar{t}$ production rates ($\mathrm{aN^3LO}$)
  - First NNLO QCD results for $t\bar{t}H$ and $t\bar{t}W$
  - Soft-gluon resummation for several $t\bar{t} + X$ channels
  - Full off-shell calculations, in some cases with complete NLO corrections
  - Improvements in PS matching: resonance-aware, MEC …
- Off-shell computations for multi-leg processes are CPU intensive
  - Most of them are NLO fixed-order results $\rightarrow$ *parton level*
  - Upgrading to NLO+PS accuracy is *computational* rather than *conceptual* problem

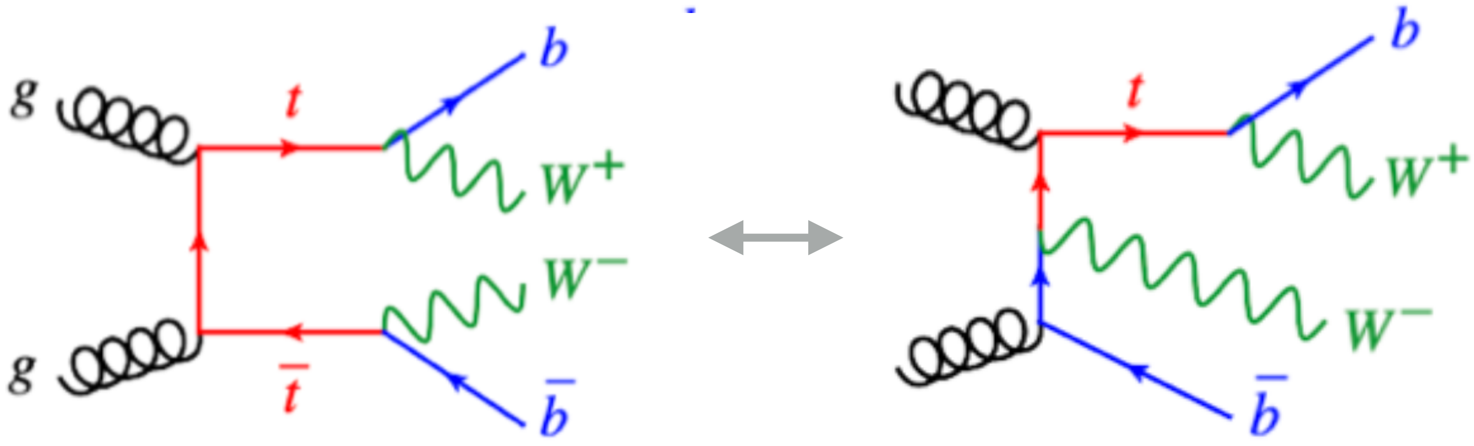
Thank you for your attention

Backup slides

Single-resonant production (tW)

- Beyond LO: overlapping $t\bar{t} \leftrightarrow tW(b)$

$\Gamma_t / m_t \to 0$



(A_{2t}) (A_{1t})

- Diagram Subtraction $\to$ DS : $|A_{tWb}|^2_{DS} = |A_{2t} + A_{1t}|^2 - C_{2t}$

- Diagram Removal $\to$ DR$_1$: $|A_{tWb}|^2_{DR_1} = |A_{1t}|^2$

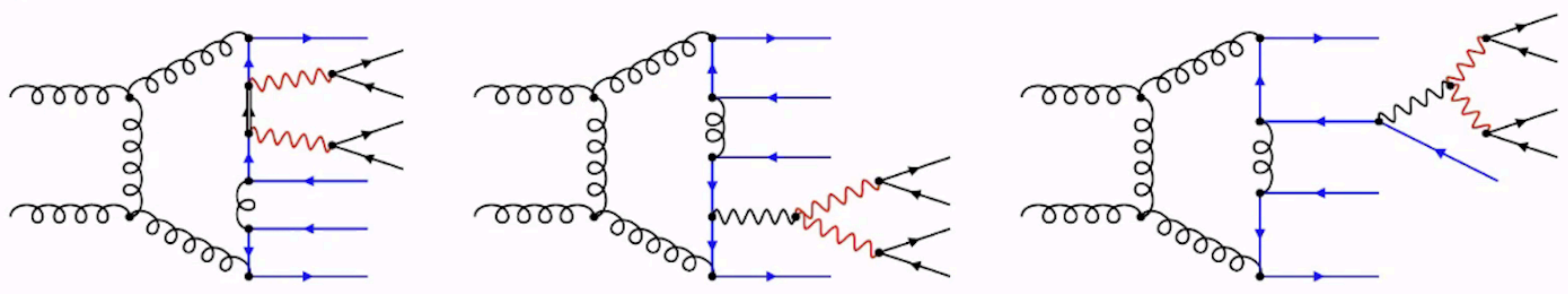
  DR$_2$: $|A_{tWb}|^2_{DR_2} = |A_{1t}|^2 + 2\mathrm{Re}(A_{1t}\, A^*_{2t})$

Technical aspects of off-shell calculations

One-loop correction type	Number of Feynman diagrams
Self-energy	93452
Vertex	88164
Box-type	49000
Pentagon-type	25876
Hexagon-type	11372
Heptagon-type	3328
Octagon-type	336
Total number [gg channel]	271528

Example: $gg \to e^+\nu_e \mu^- \bar{\nu}_\mu b\bar{b}\, b\bar{b}$

Partonic Subprocess	Number of Feynman diagrams	Number of CS Dipoles	Number of NS Subtractions
$gg \to e^+\nu_e \mu^- \bar{\nu}_\mu b\bar{b} b\bar{b} g$	41364	90	18
$q\bar{q} \to e^+\nu_e \mu^- \bar{\nu}_\mu b\bar{b} b\bar{b} g$	9576	50	10
$gq \to e^+\nu_e \mu^- \bar{\nu}_\mu b\bar{b} b\bar{b} q$	9576	50	10
$g\bar{q} \to e^+\nu_e \mu^- \bar{\nu}_\mu b\bar{b} b\bar{b} \bar{q}$	9576	50	10



[Stremmer and Worek, JHEP08 (2023) 179]

- Interplay of resonant contributions:

Di-lepton → $\sigma_{\text{NLO}} = 0.07130\,(\text{Prod}) + 0.077333\,(\text{Mix}) + 0.02863\,(\text{Dec}) = 0.1773 \text{ fb}$

44 % of σ_{NLO}

Semi-leptonic → $\sigma_{\text{NLO}} = 0.1405\,(\text{Prod}) + 0.1205\,(\text{Mix}) + 0.03629\,(\text{Dec}) = 0.2973 \text{ fb}$

40 % of σ_{NLO}