DIS2026

Modelling top-quark decays in $t\bar{t}t\bar{t}$ at the LHC

Manal Alsairafi

Alsairafi, Dimitrakopoulos, Worek Phys. Rev. D 112, 114002

DFG Deutsche Forschungsgemeinschaft

Research Training Group Physics of the Heaviest Particles at the LHC

RWTH AACHEN UNIVERSITY

TTK Institute for Theoretical Particle Physics and Cosmology

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

Goal

Compare NLO (fixed-order) to NLO+PS for $t\bar{t}t\bar{t}$ with top decays

→ How well do parton showers reproduce higher order effects in top-quark decays?

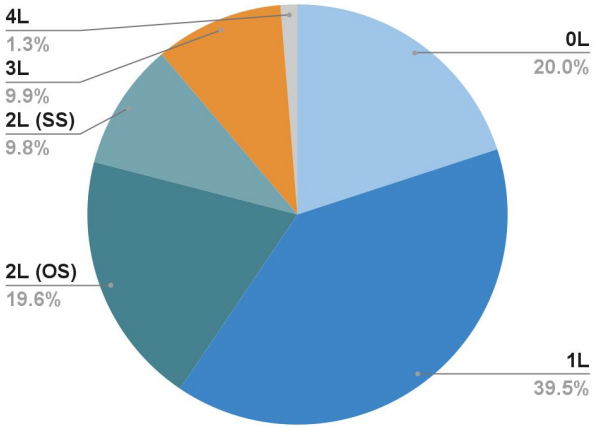
→ Which observables and regions of phase space are sensitive to parton showers?

→ What are the effects of including matrix element corrections in NLO+PS predictions?

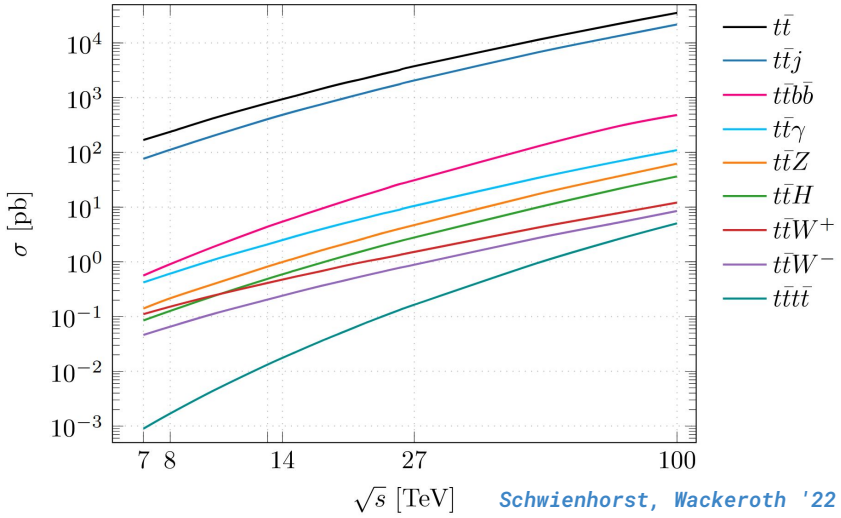
Why four tops?

- Four top production is an extremely rare 2 → 12 process

$$\sigma^{\mathrm{NLO}}_{t\bar{t}t\bar{t}}(\mathrm{LHC}_{14\mathrm{TeV}}) = 16.87^{+4.04(+24\%)}_{-4.26(-25\%)}\ \mathrm{fb}\,.$$ *Bevilacqua, Worek '12*



4 top BRs
Manganelli, Quinnan '22



Schwienhorst, Wackeroth '22

- Good test for the standard model (QCD and parton shower effects)
- Sensitive to new physics models due to large top mass and rarity

Observation of four top production

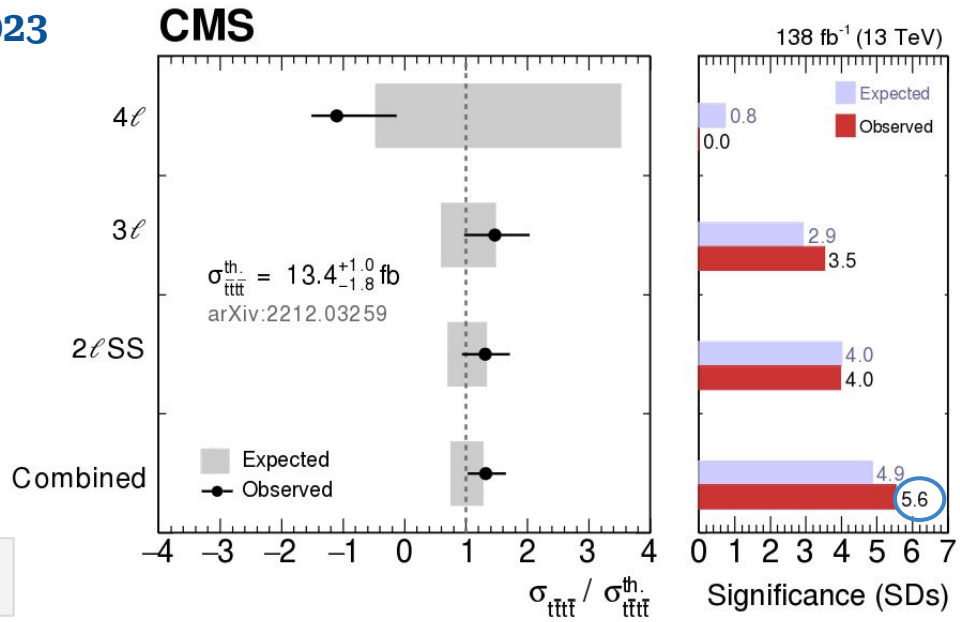
Discovery of four top production in 2023

CMS '23, ATLAS '23

Three different signal regions were taken into account:

- 4-lepton channel
- 3-lepton channel
- 2lSS channel

Observed significance of 5.6σ for CMS



CMS '23

Four tops – Theory Status

First NLO QCD predictions for 4 stable tops
Bevilacqua, Worek '12
Maltoni, Pagani, Tsinikos '16

Complete-NLO predictions for 4 stable tops with sub-leading effects
Frederix, Pagani, Zaro '18

NLO QCD matched to parton shower (NLO+PS)
Ježo, Kraus '22

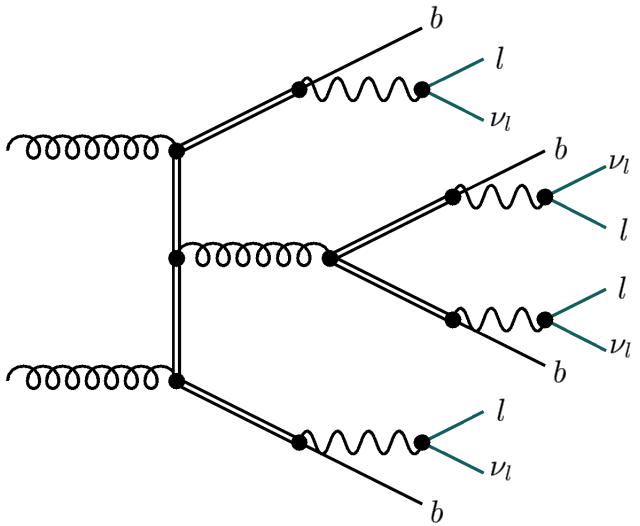
Threshold resummation for the production of four top quarks
van Beekveld, Kulesza, Valero '22
van Beekveld, Kulesza, Lupattelli, Saracco '25

NLO QCD predictions in perturbative QCD in the 4 and 3 lepton channels
Dimitrakopoulos, Worek '24
Dimitrakopoulos, Worek '25

Modelling top-quark decays at fixed-order NLO(QCD) vs. matched to PS
Alsairafi, Dimitrakopoulos, Worek '25

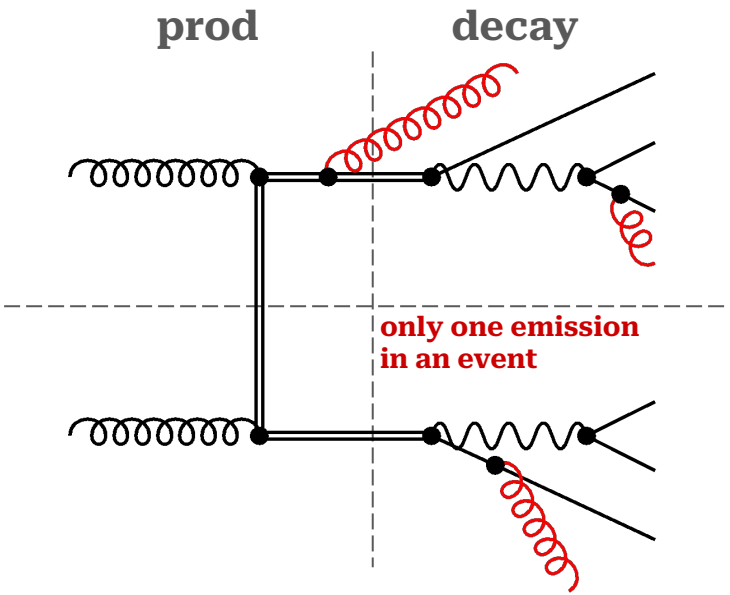
The 4-lepton Channel

$$p\ p \to l^- \bar{\nu}_l l^+ \nu_l l^- \bar{\nu}_l l^+ \nu_l\ \bar{b}\ b\ \bar{b}\ b$$

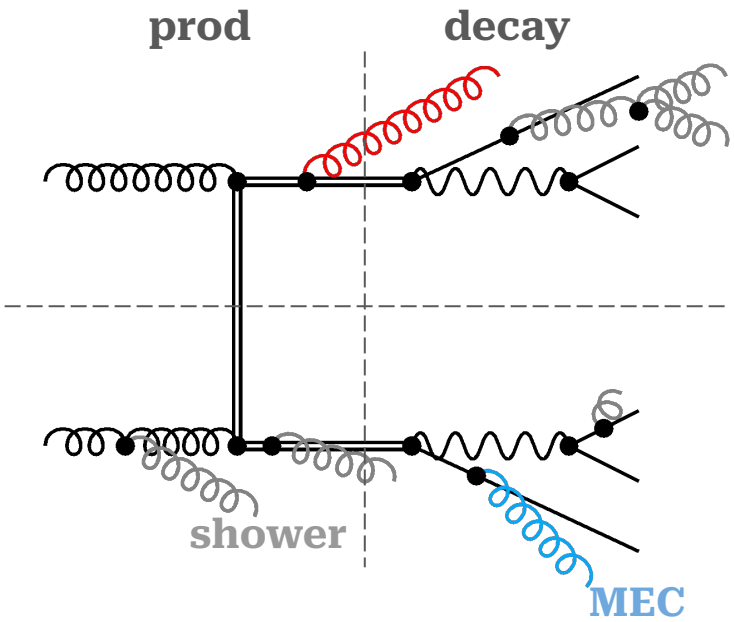


Fixed Order vs. Matching to PS

Fixed order - NWA NLO(QCD)



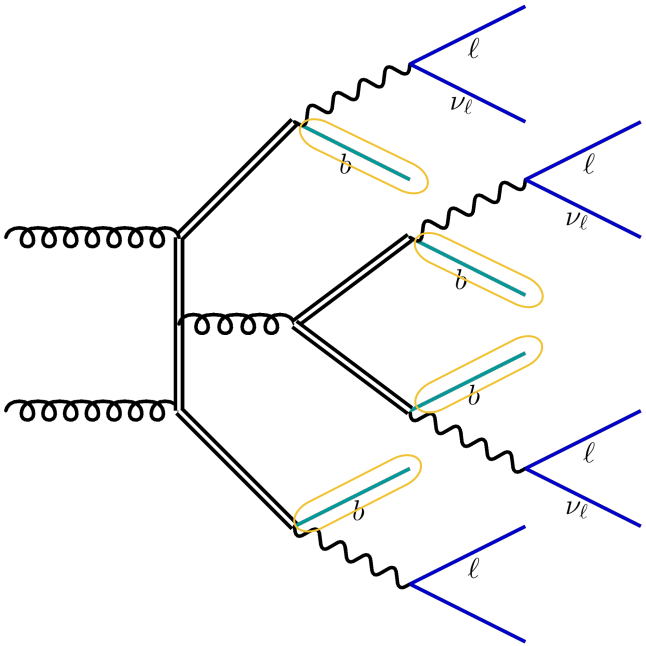
Matching to PS - NLO(QCD)+PS



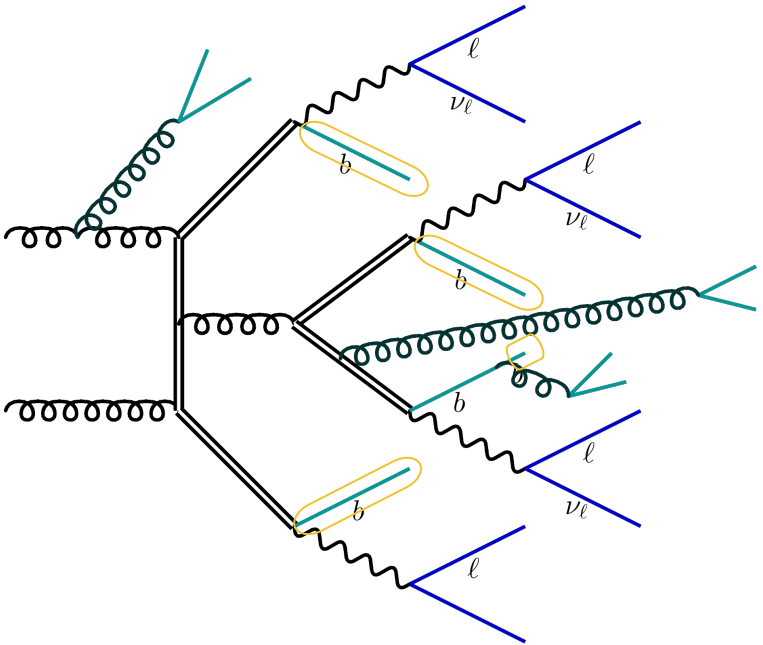
Diagrams created via FeynGame: *Harlander, Klein, Lipp '20*

Fixed Order vs. Matching to PS

Fixed order



Matching to PS



Diagrams created via FeynGame: *Harlander, Klein, Lipp '20*

Integrated Cross Section

Theoretical Approach	σ [ab]	$+\delta^{\text{scale}}$	$-\delta^{\text{scale}}$	$+\delta^{\text{match}}$	$-\delta^{\text{match}}$	$\sigma/\sigma_{\text{NWA}_{\text{exp}}}$
Fixed-Order NLO						
NWA_{exp}	5.170(3)	+12%	-20%	-	-	1.0000
NLO+PS without b-Jet Identification						
MC@NLO + PS	4.891(8)	+15%	-21%	+1.1%	-0.7%	0.9460
MC@NLO + PS $\oplus$ MEC	5.098(8)	+15%	-21%	+0.7%	-0.5%	0.9861
POWHEG + PS	4.820(6)	+15%	-21%	+0.0%	-0.5%	0.9323
POWHEG + PS $\oplus$ MEC	5.024(6)	+15%	-21%	+0.0%	-0.5%	0.9718
NLO+PS with b-Jet Identification						
MC@NLO + PS	4.708(7)	+15%	-21%	+0.8%	-0.4%	0.9106
MC@NLO + PS $\oplus$ MEC	4.923(8)	+15%	-21%	+0.5%	-0.5%	0.9522
POWHEG + PS	4.656(6)	+15%	-21%	+0.1%	-0.2%	0.9006
POWHEG + PS $\oplus$ MEC	4.865(6)	+15%	-21%	+0.0%	-0.2%	0.9410

$$\sqrt{s} = 13.6 \text{ TeV}$$

$$\mu_R = \mu_F = \frac{1}{4} E_T$$

Fixed-order NLO:

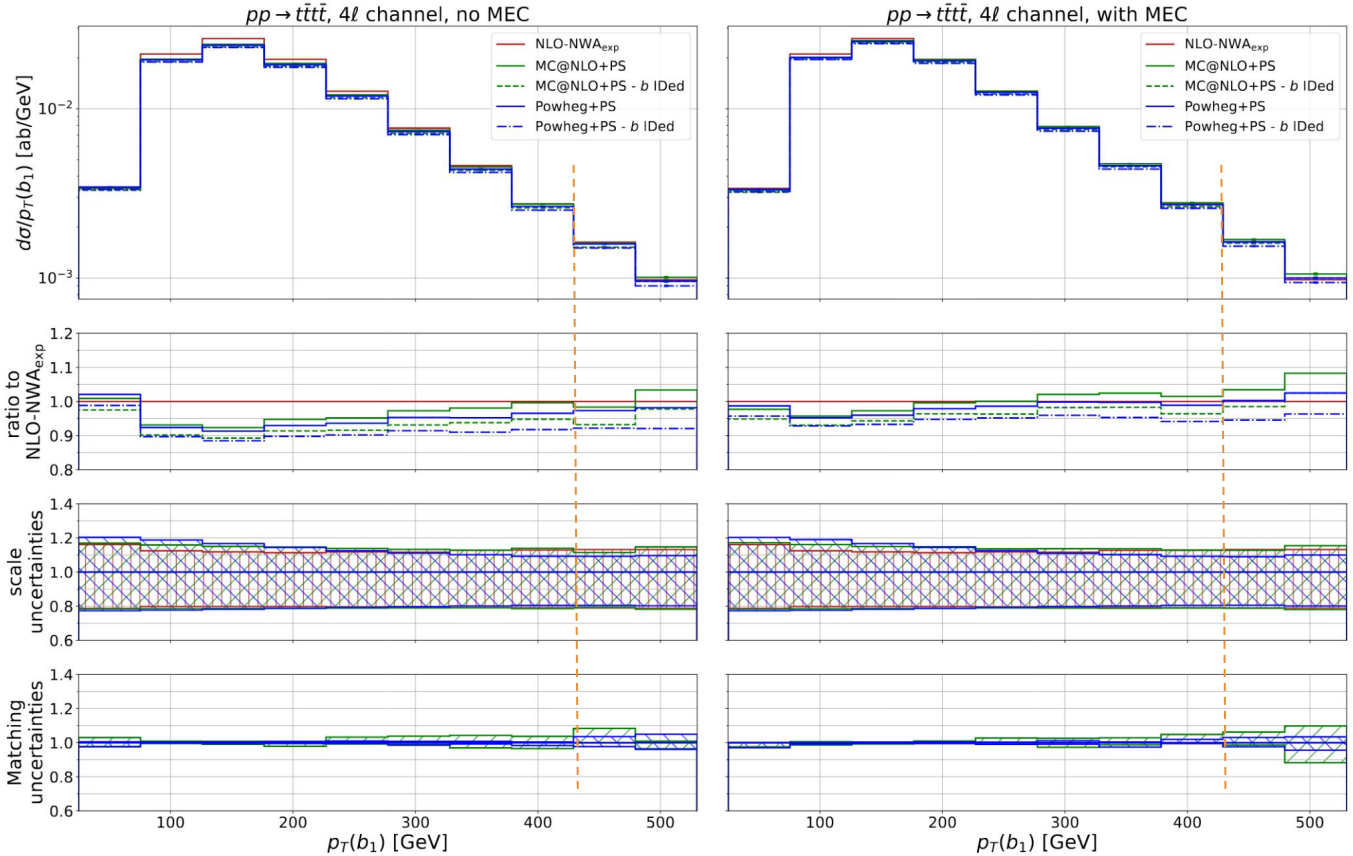
$$E_T = \sum_{t_1, \bar{t}_1, t_2, \bar{t}_2} m_T$$

NLO+PS:

$$E_T = \sum_{t_1, \bar{t}_1, t_2, \bar{t}_2, j} m_T$$

Projected HL-LHC statistical uncertainties ~16-18%

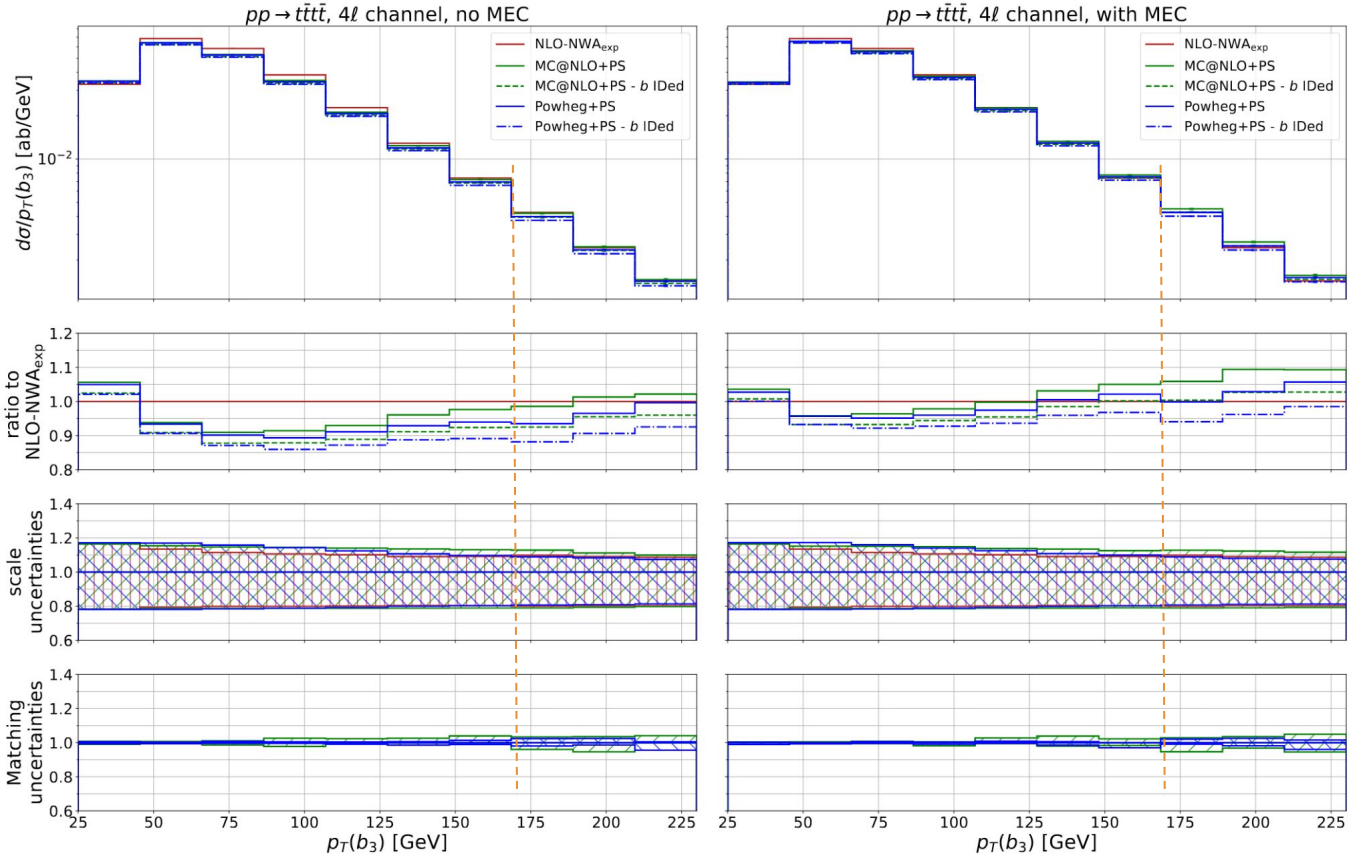
Differential Distributions



Indeed a better agreement with fixed-order predictions after MEC.

$\sqrt{s} = 13.6$ TeV

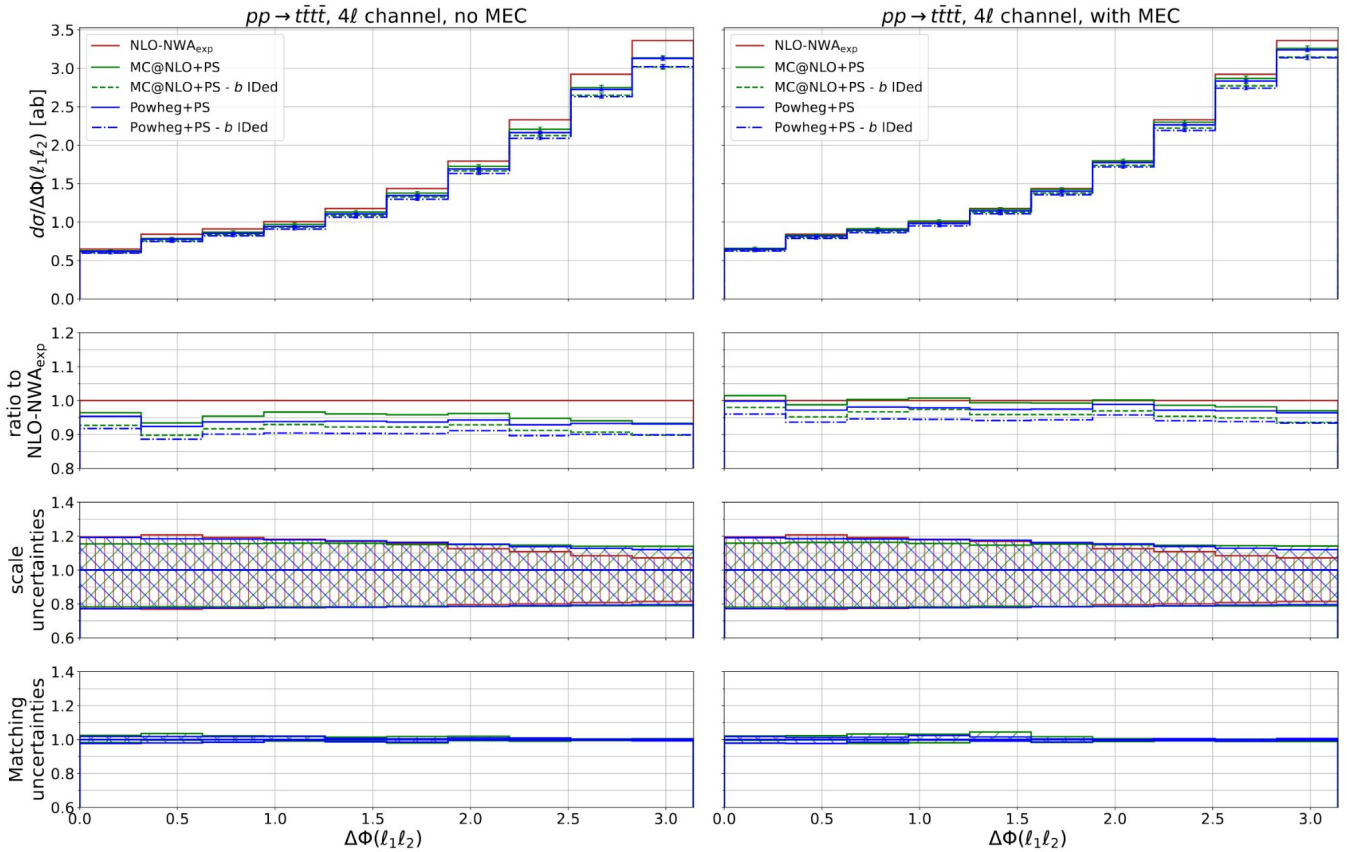
Differential Distributions



b jet identification matters.

$\sqrt{s} = 13.6$ TeV

Differential Distributions



Angular distributions (sensitive to spin correlations) agree in shape

$\sqrt{s} = 13.6$ TeV

Summary

A comparative study between NLO (fixed-order) and NLO+PS has been performed

- Agreement within the theoretical uncertainties between the different predictions
- Inclusion of MEC in NLO+PS improve the predictions
  - At the integrated level, their impact was up to **5%**
  - At the differential level a **10%-15%** difference in some phase space regions was observed (on the central values)
  - MEC partially recover higher order effects in the decays

Back-up Slides

Fixed Order - Process Description

NLO production & LO decays

$$d\sigma^{\mathrm{NLO}}_{\mathrm{full}} = d\sigma^{\mathrm{NLO}}_{t\bar{t}t\bar{t}} \times \frac{d\Gamma^0_t}{\Gamma^{\mathrm{NLO}}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\mathrm{NLO}}_t} \times \frac{d\Gamma^0_t}{\Gamma^{\mathrm{NLO}}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\mathrm{NLO}}_t} + d\sigma^{\mathrm{LO}}_{t\bar{t}t\bar{t}} \times \frac{d\Gamma^1_t}{\Gamma^{\mathrm{NLO}}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\mathrm{NLO}}_t} \times \frac{d\Gamma^0_t}{\Gamma^{\mathrm{NLO}}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\mathrm{NLO}}_t}$$

$$+ d\sigma^{\mathrm{LO}}_{t\bar{t}t\bar{t}} \times \frac{d\Gamma^0_t}{\Gamma^{\mathrm{NLO}}_t} \times \frac{d\Gamma^1_{\bar{t}}}{\Gamma^{\mathrm{NLO}}_t} \times \frac{d\Gamma^0_t}{\Gamma^{\mathrm{NLO}}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\mathrm{NLO}}_t} + d\sigma^{\mathrm{LO}}_{t\bar{t}t\bar{t}} \times \frac{d\Gamma^0_t}{\Gamma^{\mathrm{NLO}}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\mathrm{NLO}}_t} \times \frac{d\Gamma^1_t}{\Gamma^{\mathrm{NLO}}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\mathrm{NLO}}_t}$$

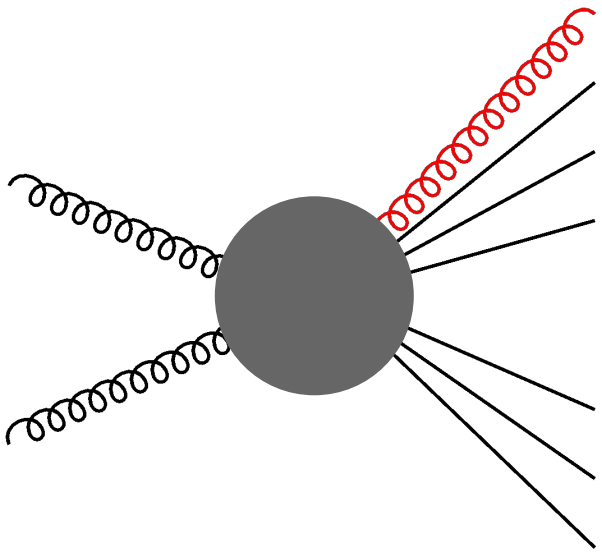
LO production & NLO decays

$$+ d\sigma^{\mathrm{LO}}_{t\bar{t}t\bar{t}} \times \frac{d\Gamma^0_t}{\Gamma^{\mathrm{NLO}}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\mathrm{NLO}}_t} \times \frac{d\Gamma^0_t}{\Gamma^{\mathrm{NLO}}_t} \times \frac{d\Gamma^1_{\bar{t}}}{\Gamma^{\mathrm{NLO}}_t}.$$

Expansion of $d\sigma = d\sigma_{tt\bar{t}\bar{t}} \times \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t}$

$$\left.\begin{aligned} d\sigma_{tt\bar{t}\bar{t}} &= d\sigma^{(0)}_{tt\bar{t}\bar{t}} + \alpha_s d\sigma^{(1)}_{tt\bar{t}\bar{t}} + \mathcal{O}(\alpha_s^2) \\ d\Gamma_t &= d\Gamma^{(0)}_t + \alpha_s d\Gamma^{(1)}_t + \mathcal{O}(\alpha_s^2) \\ \Gamma^{\mathrm{NLO}}_t &= \Gamma^{(0)}_t + \alpha_s \Gamma^{(1)}_t \end{aligned}\right\} \boxed{d\sigma^{\mathrm{NLO}}_{\mathrm{exp}}} = d\sigma^{\mathrm{NLO}} = d\sigma^{\mathrm{NLO}}_{\mathrm{full}} \times \left(\frac{\Gamma^{\mathrm{NLO}}_t}{\Gamma^{\mathrm{LO}}_t}\right)^4 - d\sigma^{\mathrm{LO}} \times \frac{4(\Gamma^{\mathrm{NLO}}_t - \Gamma^{\mathrm{LO}}_t)}{\Gamma^{\mathrm{LO}}_t}$$

Fixed Order – full off-shell?



The full off-shell effects have been studied at the LO level.
Observables with a kinematic edge, eg. $M(l^+b)$, $M(t)$, are sensitive

Dimitrakopoulos, Worek '24

Diagrams created via FeynGame: *Harlander, Klein, Lipp '20*

Fixed Order vs. Matching to PS

Fixed order

HELAC-NLO
Bevilacqua, Czakon, Garzelli, van Hameren, Kardos, Papadopoulos, Pittau, Worek '11

- **HELAC-DIPOLES**
  Czakon, Papadopoulos, and Worek '09, Bevilacqua, Czakon, Papadopoulos, Pittau, and Worek '09, Bevilacqua, Czakon, Kubocz, and Worek '13
- **HELAC-1LOOP**
  Ossola, Papadopoulos, and Pittau '08, van Hameren, Papadopoulos, and Pittau '09, van Hameren '11

HEPlot
G. Bevilacqua

Matching to PS

MadGraph5_aMC@NLO
Alwall, Frederix, Frixione, Hirschi,Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro '14

POWHEG BOX
Nason '04
Frixione, Nason, Oleari '07
Alioli, Nason, Oleari, Re '10

Pythia8 *arXiv:2203.11601*

Matrix Element Corrections
Frixione, Amoroso, Mrenna '23

Rivet[1] + FastJet[2] + HepMC3[3]
[1]Buckley, Butterworth, Grellscheid, Hoeth, Lonnblad, Monk, Schulz, and Siegert '13
[1]Bierlich et al. '20
[2]Cacciari and Salam '06
[2]Cacciari, Salam, and Soyez '12
[3]Buckley, Ilten, Konstantinov, Lönnblad, Monk, Pokorski, Przedzinski, and Verbytskyi '21

Computational Setup

Parameters

$$G_\mu = 1.1663787 \cdot 10^{-5}\ \text{GeV}^{-2}\,, \qquad m_t = 172.5\ \text{GeV}\,,$$
$$m_W = 80.379\ \text{GeV}\,, \qquad m_Z = 91.1876\ \text{GeV}.$$

W and t decay widths

$$\Gamma_t^{\text{LO}} = 1.4806\ \text{GeV} \qquad \Gamma_W^{\text{LO}} = 2.04526\ \text{GeV}$$
$$\Gamma_t^{\text{NLO}} = 1.3535983\ \text{GeV} \qquad \Gamma_W^{\text{NLO}} = 2.0972\ \text{GeV}$$

W width reweighing - for the 4 lepton channel

$$\left(\frac{BR^{NLO}(W^\pm \to l_i\nu_i)}{BR^{LO}(W^\pm \to l_i\nu_i)}\right)^4 = 0.903843211$$

Computational Setup

Renormalisation and factorisation scales

- Dynamical scale $\mu_0 = E_T/4$
- Scale variation

$$\left(\frac{\mu_R}{\mu_0}, \frac{\mu_F}{\mu_0}\right) = \{(2,1), (0.5,1), (1,2), (1,1), (1,0.5), (2,2), (0.5,0.5)\}$$

Cuts

$$p_{T,\ell} > 25 \text{ GeV}, \quad |y_\ell| < 2.5, \quad \Delta R_{\ell\ell} > 0.4,$$
$$p_{T,b} > 25 \text{ GeV}, \quad |y_b| < 2.5, \quad \Delta R_{bb} > 0.4,$$
$$p_{T,j} > 25 \text{ GeV}, \quad |y_j| < 2.5, \quad \Delta R_{bj} > 0.4.$$

Matching to PS - Computational Setup

Shower starting scale

- **For MC@NLO:**

  $\mu_Q = E_T/2$, variation by factors of 2 and 0.5

- **For POWHEG:**

$$h_{\text{damp}} = \frac{H_T}{4}\,, \qquad h_{\text{bornzero}} = 5\,,$$

$$(h_{\text{damp}}, h_{\text{bornzero}}) = \left\{\left(\frac{H_T}{4}, 5\right), \left(\frac{H_T}{4}, 2\right), \left(\frac{H_T}{4}, 5\right), \left(\frac{H_T}{8}, 10\right), \left(\frac{H_T}{2}, 5\right)\right\}$$

Matrix Element Corrections : Pythia8

Interface to MC@NLO or POWHEG
Stefano Frixione, Simone Amoroso, Stephen Mrenna '23

- no MEC settings
  - `SpaceShower:MEcorrections = off`
  - `TimeShower:MEcorrections = off`
- Decay MEC settings
  - `SpaceShower:MEcorrections = off`
  - `TimeShower:MEcorrections = on`
  - `TimeShower:MEextended = off`
  - `TimeShower:MEafterFirst = on/off`

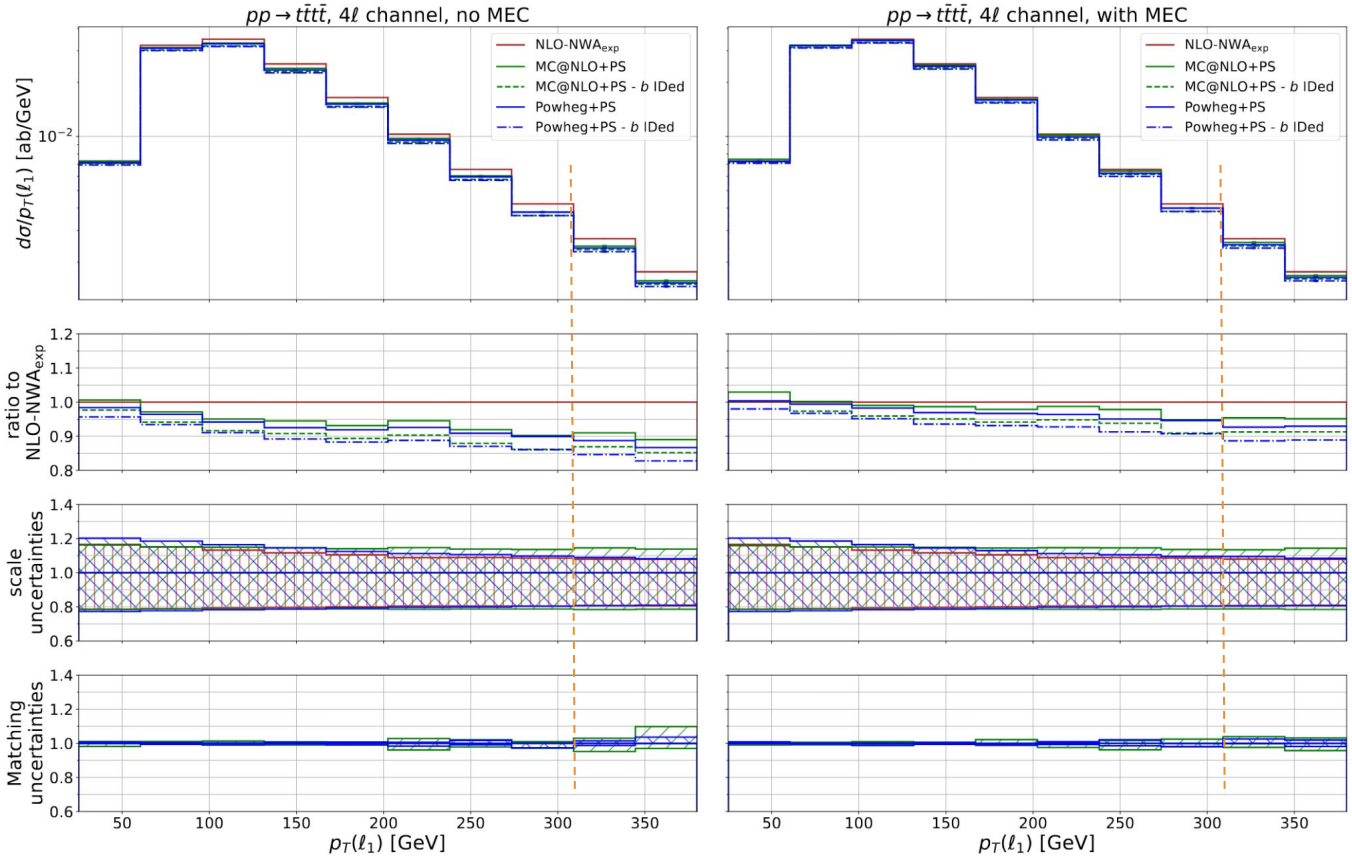
`On` : use equivalent ME
`Off` : use exactly matching ME

Relevant exact MEC : t → bWg & V → qqg

Off → ensure no double counting

`On` : MEC to emissions after the first, for dipole ends that did not yet radiate

Differential Distributions



QCD PS impact lepton kinematics.

$\sqrt{s} = 13.6$ TeV