ttH & tH report

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Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

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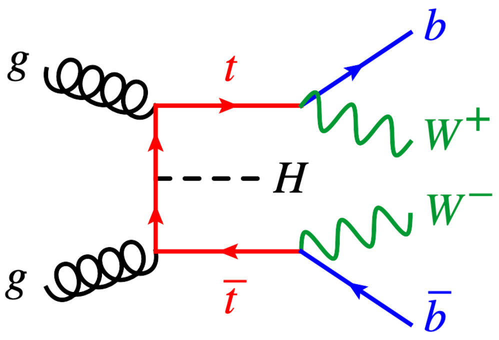
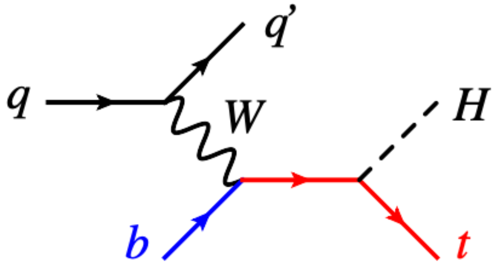
Activities of the Group

Three Main Areas:

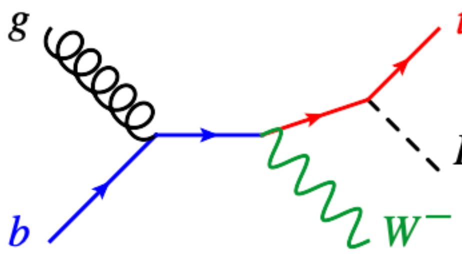
- Normalisation for signal process $pp \to ttH/tH$ $\Rightarrow$ *Ongoing common project within the LHCHWG*



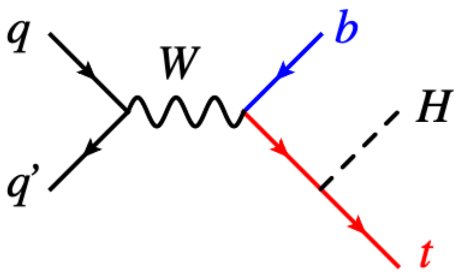
ttH



tH: t-channel



tWH



tH: s-channel

- Modelling of the fiducial phase-space regions for signal process $pp \to ttH/tH$

- Modelling of SM background processes
  - $pp \to ttbb$ & $pp \to ttjj$ & $pp \to ttcc$ $\Rightarrow$ No observation yet in the $pp \to ttH \to ttbb$ channel
  - $pp \to tt\gamma\gamma$
  - $pp \to ttW$ & $pp \to ttZ$

Not a Summary Talk of the State of the Art in This Field

Normalisation

PHYSICAL REVIEW LETTERS **130,** 111902 (2023)

Higgs Boson Production in Association with a Top-Antitop Quark Pair in Next-to-Next-to-Leading Order QCD

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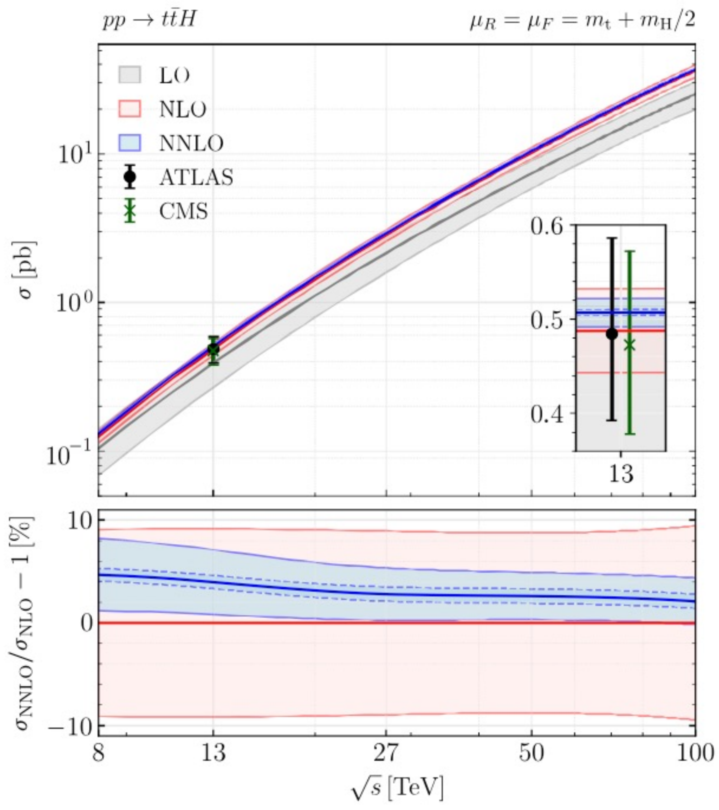
(Received 24 October 2022; revised 8 February 2023; accepted 9 February 2023; published 16 March 2023)

The associated production of a Higgs boson with a top-antitop quark pair is a crucial process at the LHC since it allows for a direct measurement of the top-quark Yukawa coupling. We present the computation of the radiative corrections to this process at the next-to-next-to-leading order (NNLO) in QCD perturbation theory. This is the very first computation for a $2 \to 3$ process with massive colored particles at this perturbative order. We develop a soft Higgs boson approximation for loop amplitudes, which enables us to reliably quantify the impact of the yet unknown two-loop contribution. At the center-of-mass energy $\sqrt{s} = 13$ TeV, the NNLO corrections increase the next-to-leading order result for the total cross section by about 4% and lead to a significant reduction of perturbative uncertainties.

DOI: 10.1103/PhysRevLett.130.111902



σ (pb)	$\sqrt{s} = 13$ TeV	$\sqrt{s} = 100$ TeV
σ_{LO}	$0.3910^{+31.3\%}_{-22.2\%}$	$25.38^{+21.1\%}_{-16.0\%}$
σ_{NLO}	$0.4875^{+5.6\%}_{-9.1\%}$	$36.43^{+9.4\%}_{-8.7\%}$
σ_{NNLO}	$0.5070(31)^{+0.9\%}_{-3.0\%}$	$37.20(25)^{+0.1\%}_{-2.2\%}$

- @ HL-LHC uncertainties are expected to reach 2% level
- Exact 2-loop amplitudes for ***ttH*** production are still out of reach
- This calculation relies on an approximation

@ 13 TeV: K_{NLO} = 1.25 & K_{NNLO} = 1.04

Normalisation

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The European Physical Journal C

Check for updates

Regular Article - Theoretical Physics

Associated top quark pair production with a heavy boson: differential cross sections at NLO + NNLL accuracy

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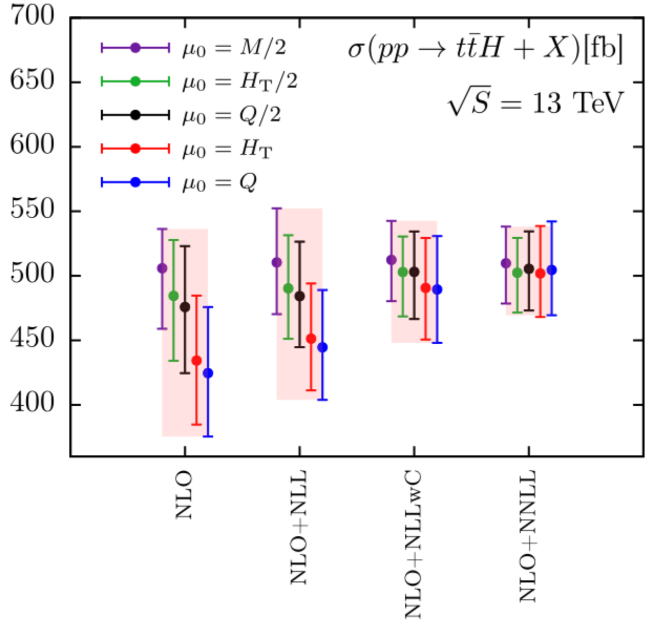
Resummation of soft-gluon emission corrections done based on SCET and direct QCD framework



JHEP

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Top-quark pair hadroproduction in association with a heavy boson at NLO+NNLL including EW corrections

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JHEP08(2019)039

$$\mathcal{K}_{\mathrm{NNLL}} = \frac{\mathrm{NLO+NNLL}}{\mathrm{NLO}}$$

Process	μ_0	NLO[fb]	NLO+NLL[fb]	NLO+NLLwC[fb]	NLO + NNLL[fb]	K_{NNLL}
$t\bar{t}H$	Q	$425^{+12.1\%}_{-11.6\%}$	$445^{+10.0\%}_{-9.2\%}$	$489^{+8.4\%}_{-8.5\%}$	$505^{+7.5\%}_{-7.0\%}$	1.19
	H_T	$434^{+11.6\%}_{-11.4\%}$	$451^{+9.5\%}_{-8.9\%}$	$491^{+7.9\%}_{-8.2\%}$	$502^{+7.3\%}_{-6.7\%}$	1.16
	$Q/2$	$476^{+9.9\%}_{-10.8\%}$	$484^{+8.7\%}_{-8.2\%}$	$503^{+6.2\%}_{-7.3\%}$	$505^{+5.7\%}_{-6.4\%}$	1.06
	$H_T/2$	$484^{+8.9\%}_{-10.4\%}$	$490^{+8.4\%}_{-8\%}$	$503^{+5.5\%}_{-6.8\%}$	$502^{+5.4\%}_{-6.1\%}$	1.04
	$M/2$	$506^{+6\%}_{-9.3\%}$	$510^{+8.2\%}_{-7.8\%}$	$512^{+5.9\%}_{-6.2\%}$	$510^{+5.6\%}_{-6.1\%}$	1.01

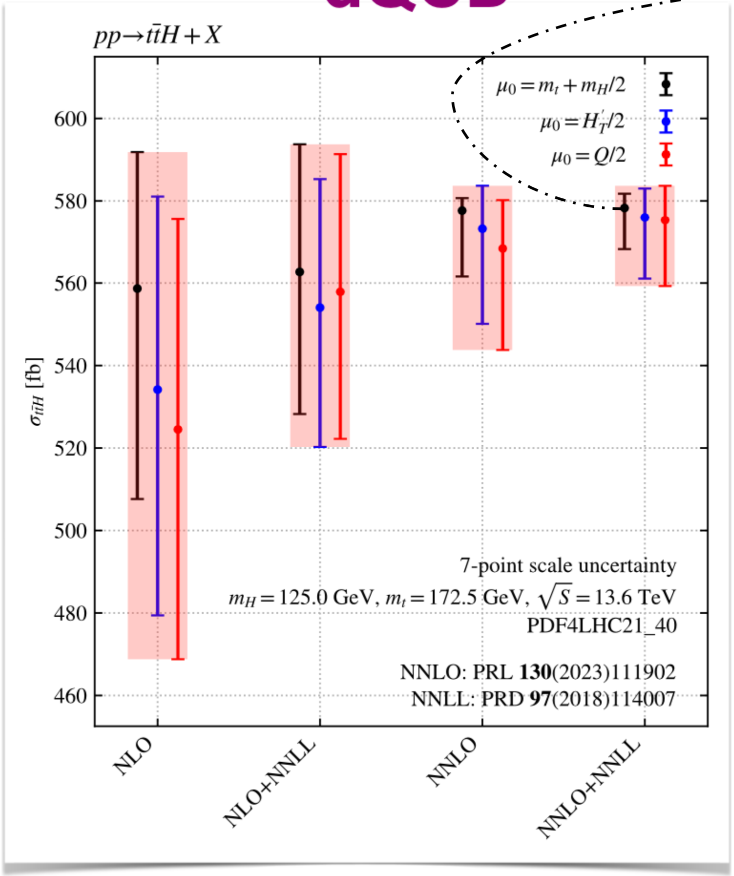
Normalisation

PRELIMINARY

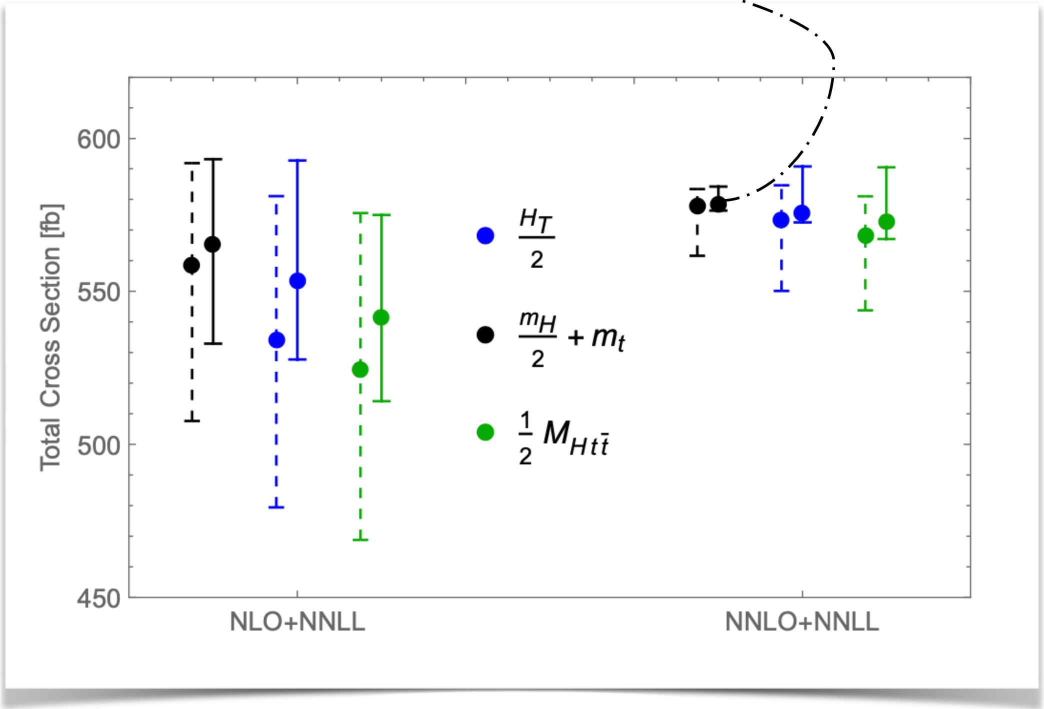
- *Common Project* ⇛ ***ttH***: resummed predictions and residual uncertainties

NNLO+NNLL

dQCD



SCET



$$\mu_0 = H_T = \sum_{i=t,\bar{t},B} m_T(i) = \sum_{i=t,\bar{t},B} \sqrt{m_i^2 + p_T^2(i)}$$

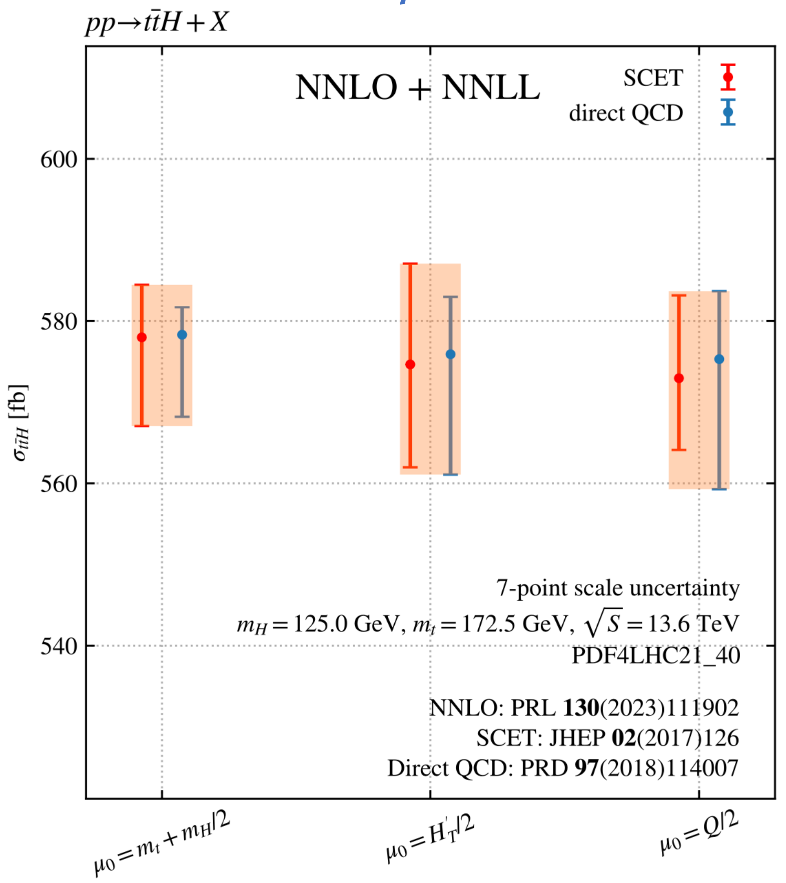
Normalisation

- Two calculations use technically very different frameworks
  - Perturbative "full" theory (QCD)
  - Effective theory (SCET)
- Both approaches rely on solving RG evolution equations, but differ in detail, organising various terms differently
- The two implemented resummation formulas agree at NNLL accuracy
- Beyond NNLL, different subsets of subleading terms which are included in the two calculations, lead to small numerical differences
- ***dQCD & SCET*** predictions for the central values agree within a few permille
- NNLL resummation results in a reduction of the theoretical error due to scale variation as well as in improved stability w.r.t. the central scale choice, compared to NNLO
- Ongoing project within the LHCHWG
  - *Understanding the differences between uncertainty estimation in the two approaches*
  - *Providing state-of-the-art theoretical predictions for ttH @ NNLO + NNLL*
  - *Plus predictions for tH production in all channels @ NLO in QCD*

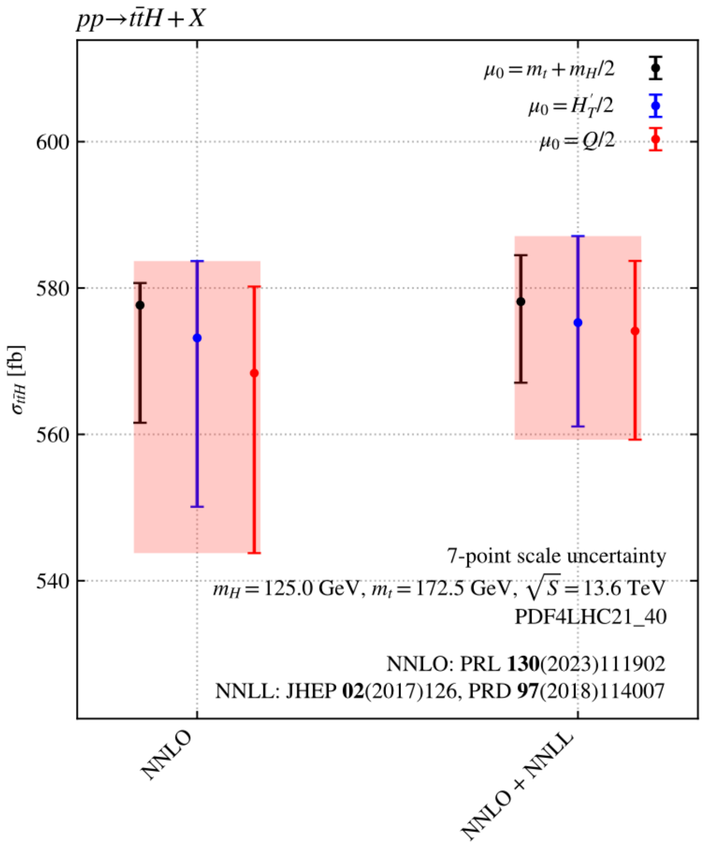
Normalisation

PRELIMINARY

Comparison



Combination



$\mu_F = \mu_R$	NNLO+NNLL
$\frac{Q}{2} = \frac{M_{t\bar{t}H}}{2}$	574.1 + 9.6 - 14.8 fb
$\frac{H_T}{2}$	575.3 +11.8 - 14.2 fb
$m_t + \frac{m_H}{2}$	578.1 + 6.3 - 11.1 fb

- Central value of combined result taken as average of ***dQCD & SCET*** results for $\mu_F = \mu_R$
- Combined uncertainties determined from envelope over ***dQCD & SCET*** scale variation error bands
- Effort on both sides to have similar treatment of the scale variations

Normalisation ⇒ Fiducial Phase-Space Regions

- Higher order corrections for on-shell top quarks are important
- Give general idea about size of higher order effects & uncertainties
- Can not provide reliable description of top-quark decay products and radiation pattern
- Can not provide predictions in fiducial phase-space regions
- For more realistic studies we need top-quark decays & higher orders effects in top-quark decays

Differential Distributions in Fiducial Regions

- Standard for TTH
  - NLO QCD matched to parton shower programs via **POWHEG** or **aMC@NLO** method with LO spin correlations

- Also Available

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NLO QCD corrections to off-shell top-antitop production with leptonic decays in association with a Higgs boson at the LHC

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Abstract: We compute the hadronic production of top-antitop pairs in association with a Higgs boson at next-to-leading-order QCD, including the decay of the top and antitop quark into bottom quarks and leptons. Our computation is based on full leading and next-to-leading-order matrix elements for $\mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}\mathrm{H}(\mathrm{j})$ and includes all non-resonant contributions, off-shell effects and interferences. Numerical results for the integrated cross section and several differential distributions are given for the LHC operating at 13 TeV using a fixed and a dynamical factorization and renormalization scale. The use of the dynamical instead of the fixed scale improves the perturbative stability in high-energy tails of most distributions, while the integrated cross section is hardly affected differing by only about one per cent and leading to almost the same K factor of about 1.17.

Keywords: NLO Computations, Monte Carlo Simulations

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Higgs production in association with off-shell top-antitop pairs at NLO EW and QCD at the LHC

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Abstract: We present NLO electroweak corrections to Higgs production in association with off-shell top-antitop quark pairs. The full process $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}\mathrm{H}$ is considered, and hence all interference, off-shell, and non-resonant contributions are taken into account. The electroweak corrections turn out to be below one per cent for the integrated cross section but can exceed 10% in certain phase-space regions. In addition to its phenomenological relevance, the computation constitutes a major technical achievement as the full NLO virtual corrections involving up to 9-point functions have been computed exactly. The results of the full computation are supported by two calculations in the double-pole approximation. These also allow to infer the effect of off-shell contributions and emphasise their importance especially for the run II of the LHC. Finally, we present combined predictions featuring both NLO electroweak and QCD corrections in a common set-up that will help the experimental collaborations in their quest of precisely measuring the aforementioned process.

Keywords: NLO Computations

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Production and decay of the Higgs boson in association with top quarks

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Abstract: We report on the calculation of the next-lo-leading order QCD corrections to Higgs boson production and decay in association with top quarks. We consider leptonic decays of top quarks leading to the hadronic process $pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\, b\bar{b}\, H\,(H \to X)$ at the LHC with $\sqrt{s} = 13$ TeV. All resonant as well as non-resonant Feynman diagrams, interferences and off-shell effects are included for the top quark and W gauge boson. Decays of the Higgs boson, on the other hand, are included in the narrow-width approximation. Specifically, we consider Higgs boson decays into $b\bar{b}$, $\tau^+\tau^-$, $\gamma\gamma$ and $e^+e^-e^+e^-$. Numerical results are given at the integrated and differential fiducial level for various factorisation and renormalisation scale choices and different PDF sets. We study the main theoretical uncertainties that are associated with neglected higher order terms in the perturbative expansion and with different parametrisations of the PDFs. Furthermore, we examine the size of the off-shell effects by an explicit comparison to the calculation in the full narrow-width approximation. Finally, the impact of the contributions induced by the bottom-quark parton density is investigated.

Keywords: NLO Computations, QCD Phenomenology

ArXiv ePrint: 2111.01427

JHEP02(2022)196

Why Off-Shell Predictions

PHYSICAL REVIEW LETTERS **121,** 152002 (2018)

Probing the Quantum Interference between Singly and Doubly Resonant Top-Quark Production in *pp* Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

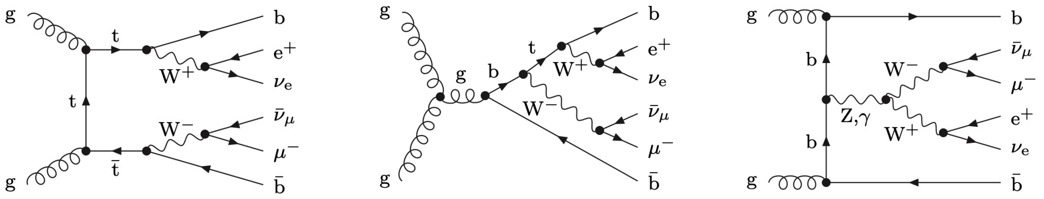
M. Aaboud *et al.*[*]
(ATLAS Collaboration)

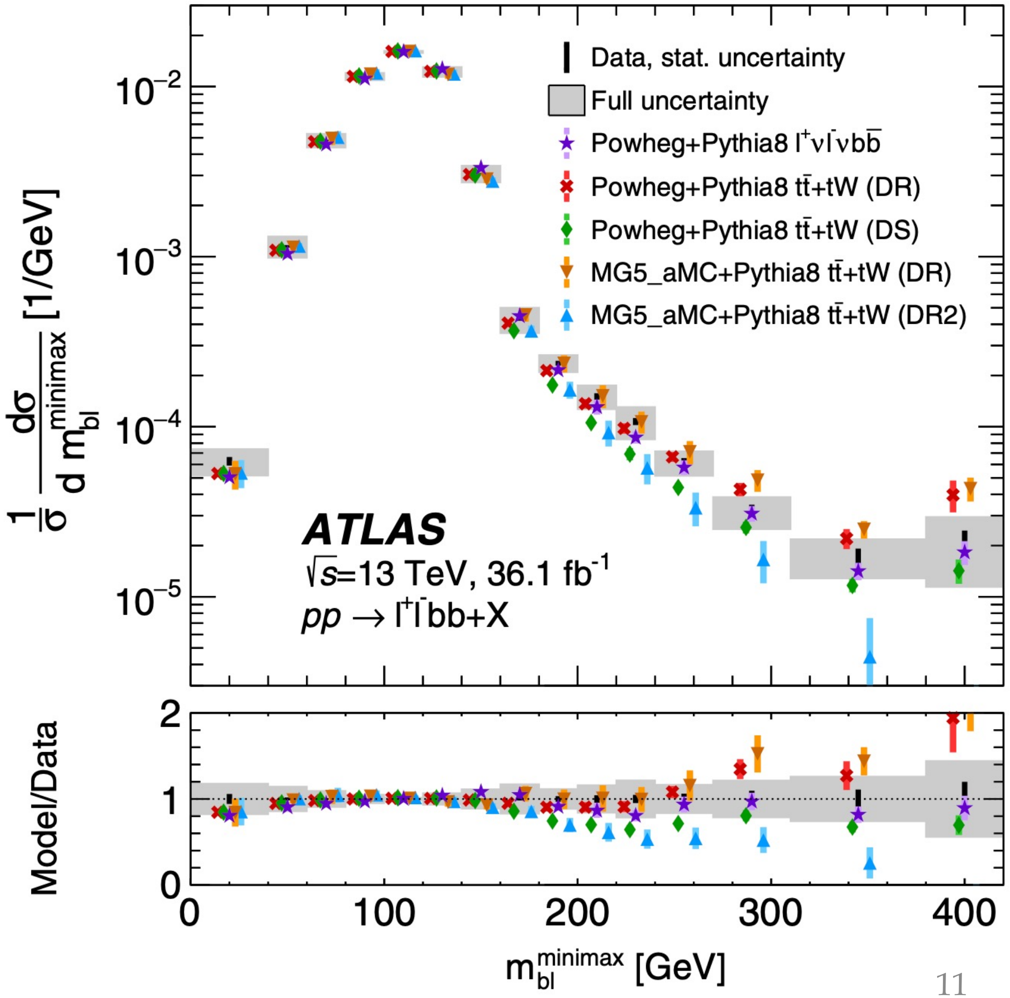
(Received 13 June 2018; revised manuscript received 6 August 2018; published 12 October 2018)

This Letter presents a normalized differential cross-section measurement in a fiducial phase-space region where interference effects between top-quark pair production and associated production of a single top quark with a W boson and a b-quark are significant. Events with exactly two leptons (ee, $\mu\mu$, or $e\mu$) and two b-tagged jets that satisfy a multiparticle invariant mass requirement are selected from 36.1 fb^{-1} of proton-proton collision data taken at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC in 2015 and 2016. The results are compared with predictions from simulations using various strategies for the interference. The standard prescriptions for interference modeling are significantly different from each other but are within 2σ of the data. State-of-the-art predictions that naturally incorporate interference effects provide the best description of the data in the measured region of phase space most sensitive to these effects. These results provide an important constraint on interference models and will guide future model development and tuning.

DOI: 10.1103/PhysRevLett.121.152002

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





Differential Distributions in Fiducial Regions

- **Standard for TTH**
  - NLO QCD matched to parton shower programs via **POWHEG** or **aMC@NLO** method with LO spin correlations

- **Also Available**

Eur. Phys. J. C (2023) 83:970
https://doi.org/10.1140/epjc/s10052-023-12154-x

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Matrix element corrections in the PYTHIA8 parton shower in the context of matched simulations at next-to-leading order

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Abstract We discuss the role of matrix element corrections (MEC) to parton showers in the context of MC@NLO-type matchings for processes that feature unstable resonances, where MEC are liable to result in double-counting issues, and are thus generally not employed. By working with PYTHIA8, we show that disabling all MEC is actually unnecessary in computations based on the narrow-width approximation, and we propose alternative MEC settings which, while still avoiding double counting, allow one to include hard-recoil effects in the simulations of resonance decays. We illustrate our findings by considering $t\bar{t}$ production at the LHC, and by comparing MadGraph5-aMC@NLO predictions with those of POWHEG- BOX and standalone PYTHIA8.

1 Introduction

The exclusive simulation of processes that feature heavy unstable particles, such as the top, W, Z, and Higgs in the Standard Model, is complicated for a variety of reasons. Conceptually, the most straightforward approach is to choose a (set of) decay channel(s) for the unstable particle(s) and compute the process where the initial and final states only include light partons and the products of such decay channels. For example, in the case of $t\bar{t}$ production, one may focus on a dilepton channel, and thus simulate (in hadronic collisions)[1]

$$pp \longrightarrow b\bar{\ell}_i\nu_i\bar{b}\ell_j\bar{\nu}_j\,, \qquad (1)$$

Eur. Phys. J. C (2024) 84:410
https://doi.org/10.1140/epjc/s10052-024-12737-2

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Matrix element corrections in top quark decays for the $t\bar{t}W^{\pm}$ process

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Abstract We present a method that allows enabling matrix element corrections (MECs) in PYTHIA8 with MC@NLO matching, without incurring double counting. MECs are an interesting feature that may contribute to the accuracy of theoretical predictions, alongside matching and merging. We directly compare our method to a specific choice of settings in PYTHIA8, which can remove double-counting for MECs in certain processes. We show results by taking the $t\bar{t}W$ process as an example. This choice allows us to study the impact of decay MECs in the 2SSℓ and 3ℓ final states. We find that jet-related observables receive these corrections unevenly throughout the phase space. They can contribute up to ±6% in certain regions.

thus potentially improving the baseline performance of parton showers. In the absence of higher-order perturbative calculations, MECs are a computationally efficient way that may enhance the accuracy of theoretical predictions and are therefore of phenomenological interest. In PYTHIA8 MECs are turned on by default, unless one is interested in MC@NLO [11,12] style matching. In this case, according to the official recommendation of the latest Pythia manual, all MEC functionalities must be turned off by the user to avoid potential double-counting. This is unfortunate, since MECs can e.g. correct resonance decays and promote them to approximate NLO QCD accuracy, which should give a better description of the radiation pattern of jet-related observables. The first goal of this paper, is to present a general method that

Differential Distributions in Fiducial Regions

- **Standard for TTH**
  - NLO QCD matched to parton shower programs via **POWHEG** or **aMC@NLO** method with LO spin correlations

- **Also Available**

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https://doi.org/10.1140/epjc/s10052-024-12836-0

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Theoretical Physics

Improving NLO QCD event generators with high-energy EW corrections

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Abstract In this work we present a new method for the combination of electroweak (EW) corrections at high energies, the so-called EW Sudakov logarithms (EWSL), and next-to-leading-order QCD predictions matched to parton-shower simulations (NLO+PS). Our approach is based on a reweighting procedure of NLO+PS events. In particular, both events with and without an extra hard emission from matrix elements are consistently reweighted via the inclusion of the corresponding EWSL contribution. We describe the technical details and the implementation in the MadGraph5_aMC@NLO framework. Via a completely automated procedure, events at this level of accuracy can be obtained for a vast class of hadroproduction processes. As a byproduct we provide results for phenomenologically relevant physical distributions from top-quark pair and Higgs boson associated production ($t\bar{t}H$) and from the associated production of three Z gauge bosons (ZZZ).

1 Introduction

After the first two runs of the Large Hadron Collider (LHC), our knowledge of the fundamental interactions of elementary particles has tremendously improved. Above all, the Higgs

Yukawa Coupling

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The European Physical Journal C

CrossMark

Regular Article - Theoretical Physics

tWH associated production at the LHC

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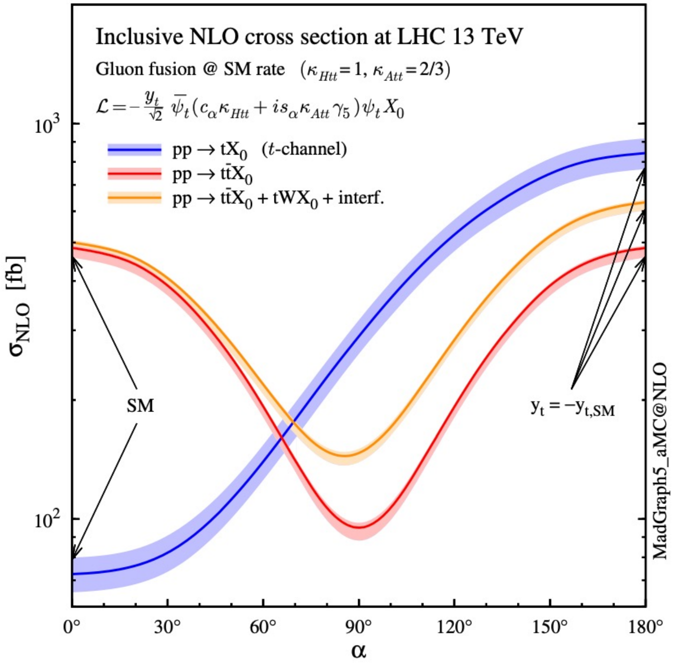
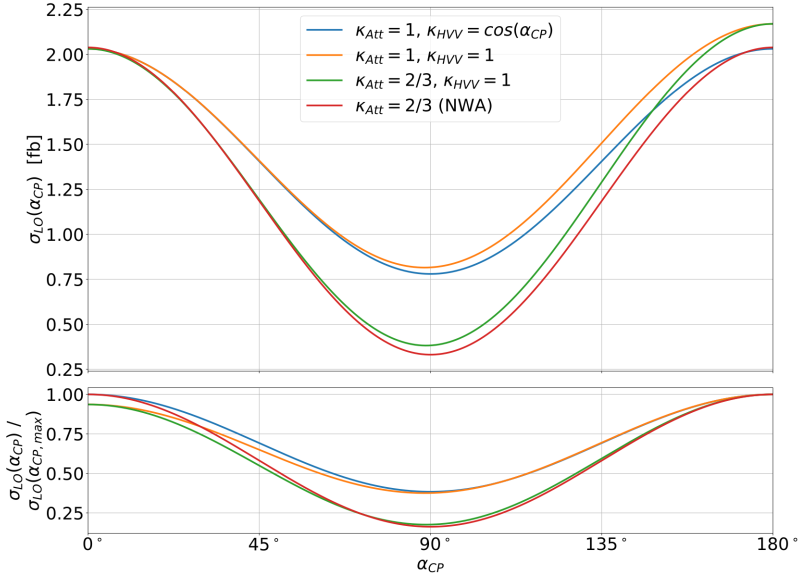
$$\alpha_{CP} \longrightarrow \pi - \alpha_{CP} \qquad Y_t \longrightarrow -Y_t$$





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$\mathcal{CP}$ structure of the top-quark Yukawa interaction: NLO QCD corrections and off-shell effects

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Abstract: Since its discovery at the Large Hadron Collider in 2012 the Higgs boson has arguably become the most famous of the Standard Model particles and many measurements have been performed in order to assess its properties. Among others, these include measurements of the Higgs boson's $\mathcal{CP}$ state which is predicted to be $\mathcal{CP}$-even. Even though a pure $\mathcal{CP}$-odd state has been ruled out, a possible admixture of a $\mathcal{CP}$-odd Higgs state has yet to be excluded. In this work we present predictions for the associated production of a leptonically decaying top quark pair and a stable Higgs boson $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}H$ with possible mixing between $\mathcal{CP}$-even and $\mathcal{CP}$-odd states at NLO in QCD for the LHC with $\sqrt{s} = 13$ TeV. Finite top-quark and gauge-boson width effects as well as all double-, single- and non-resonant Feynman diagrams including their interference effects are taken into account. We compare the behaviour of the $\mathcal{CP}$-even, -odd and -mixed scenarios for the integrated fiducial cross-sections as well as several key differential distributions. In addition, we show that both NLO corrections and off-shell effects play an important role even at the level of integrated fiducial cross-sections and that these are further enhanced in differential distributions. Even though we focus here on the Standard Model Higgs boson, the calculations could be straightforwardly applied to models that have an extended Higgs-boson sector and predict the existence of $\mathcal{CP}$-odd Higgs-like particles, such as the two-Higgs-doublet model.

Keywords: Anomalous Higgs Couplings, Higgs Properties, Higher-Order Perturbative Calculations, Top Quark

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$$\mathcal{L}_{t\bar{t}H} = -\bar{\psi}_t \frac{Y_t}{\sqrt{2}} \left(\kappa_{Ht\bar{t}} \cos(\alpha_{\rm CP}) + i\kappa_{At\bar{t}} \sin(\alpha_{\rm CP})\gamma_5\right) \psi_t H$$

$$\mathcal{L}_{HVV} = \kappa_{HVV} \left(\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu}\right) H$$

Yukawa Coupling

- $\alpha_{CP} = 0$ corresponds to the $\mathcal{CP}$-even case,
- $\alpha_{CP} = \pi/2$ corresponds to the $\mathcal{CP}$-odd case,
- $\alpha_{CP} = \pi/4$ corresponds to the $\mathcal{CP}$-mixed case.

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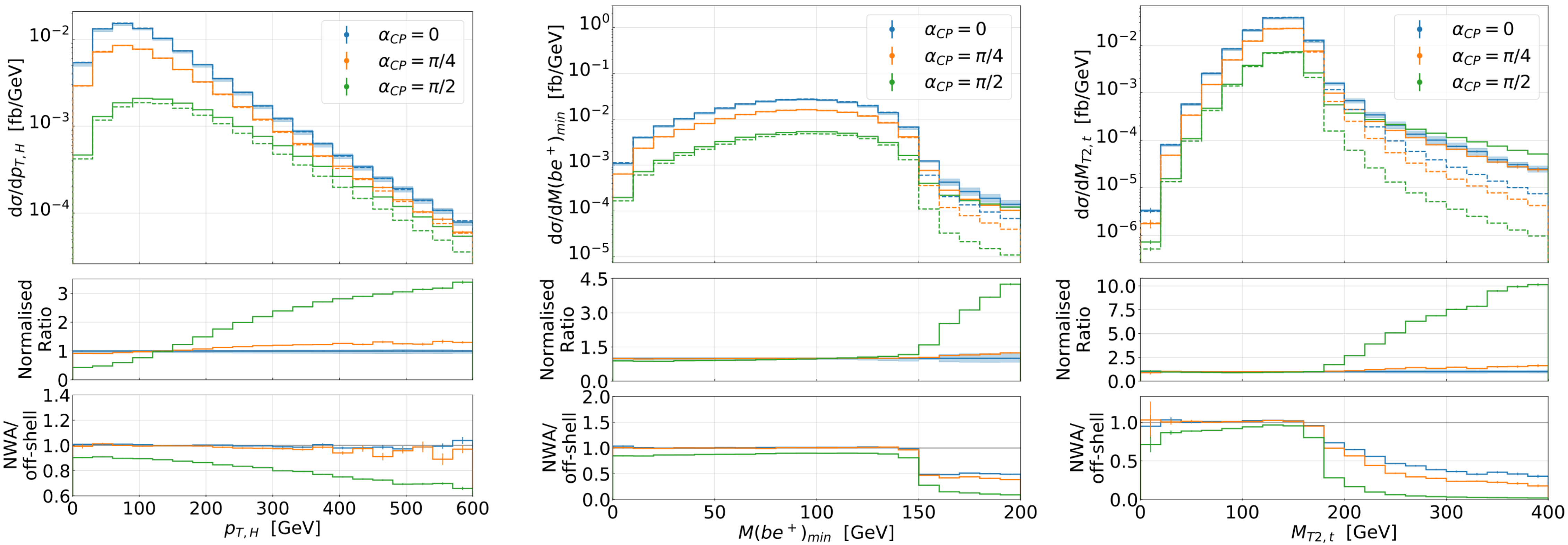

Off-Shell versus On-Shell Predictions

- Standard for TTH: NLO QCD matched to parton shower programs via **POWHEG** or **aMC@NLO method** with LO spin correlations

- Comparisons with NWA & full off-shell results
  - Assess extent to which parton shower effects can reproduce all contributions required at NLO QCD
  - Identify regions of phase space & observables sensitive to parton shower effects
  - Identify regions of phase space & observables sensitive to full off-shell effects

- Study effects of matrix element corrections for ***ttH***

- Study interference effects for ***ttH*** ➡ $|\mathcal{M}_{2tH} + \mathcal{M}_{1tH} + \mathcal{M}_{1\bar{t}H} + \mathcal{M}_{0tH}|^2$ versus $|\mathcal{M}_{2tH}|^2 + |\mathcal{M}_{1tH}|^2 + |\mathcal{M}_{1\bar{t}H}|^2$ (*DR or DS*)

- Matching of ***ttH*** with off-shell effects to parton shower programs using resonant aware matching

- Phenomenological studies for ***ttH*** with EW Sudakov logarithms & comparisons with exact NLO EW accuracy predictions

- Study impact of full off-shell effects & higher order corrections in top-quark decays on Y_t in ***ttH/tH***
  - Also at the differential cross-section level

Background Processes

- Many new results in the literature for ***pp → ttbb & pp → ttjj & pp → ttγγ & pp → ttW & pp → ttZ***

- **Possible topics:**

    - Modelling studies on ***pp → ttbb*** ➡ Five-flavour (FxFx merging scheme for ***pp → tt + jets*** production with up to 2 jets at NLO accuracy with the increased efficiency in selecting events with ***b-jets***) versus four-flavour predictions
    - Modelling studies on ***pp → ttW*** ➡ Sherpa versus FxFx, studying matrix element corrections
    - Inclusion of off-shell effects, especially singly-resonant contribution that are still largely ignored in analyses
    - Studies on ***pp → ttcc***
    - Study on disentangling bottom jets from top-quark decays from other b-jets in ***pp → ttH → ttbb & pp → ttbb***
    - …

- *No concrete plans for common projects within the LHCHWG yet ➡ Please contact us !*

arXiv:2403.14419v1 [hep-ph] 21 Mar 2024

Five-flavour scheme predictions for $t\bar{t}b\bar{b}$ at next-to-leading order accuracy

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Abstract

We compute top quark pair production in association with a bottom quark pair at the LHC within the five-flavour scheme, employing the FxFx merging scheme for $t\bar{t}$ + jets production with up to 2 jets at NLO accuracy. To enhance the selection efficiency for the events with b-jets within the inclusive five-flavour sample, we augment the generation probability of bottom quark flavours in the short-distance event generation. Our analysis reveals significant differences from NLO predictions within the four-flavour scheme.

1 Introduction

Top quark pair production in association with a bottom quark pair ($t\bar{t}b\bar{b}$) is pivotal for probing the fundamental interactions of the Standard Model and extracting crucial information about its properties [1–4]. At the Large Hadron Collider (LHC), $t\bar{t}b\bar{b}$ production serves as a significant background process across various high-energy physics phenomena, profoundly impacting the precise determination of the top quark Yukawa coupling from experimental data. Specifically, $t\bar{t}b\bar{b}$ production represents a notable background in scenarios involving the associated production of the Higgs boson with a top quark pair [5–9], followed by the Higgs decay into bottom quarks, as well as in the production of four-top quark final states [10, 11].

In the simulation of the $t\bar{t}b\bar{b}$ process, there are two primary theoretical frameworks: the four-flavour scheme (4FS) and the five-flavour scheme (5FS). The 4FS approach treats bottom quarks as massive particles, decoupled from the Parton Density Functions (PDFs) and renormalised on-shell. While, in principle straightforward to apply at fixed order [12–16], challenges arise due to the large mass difference between the top and bottom quarks.

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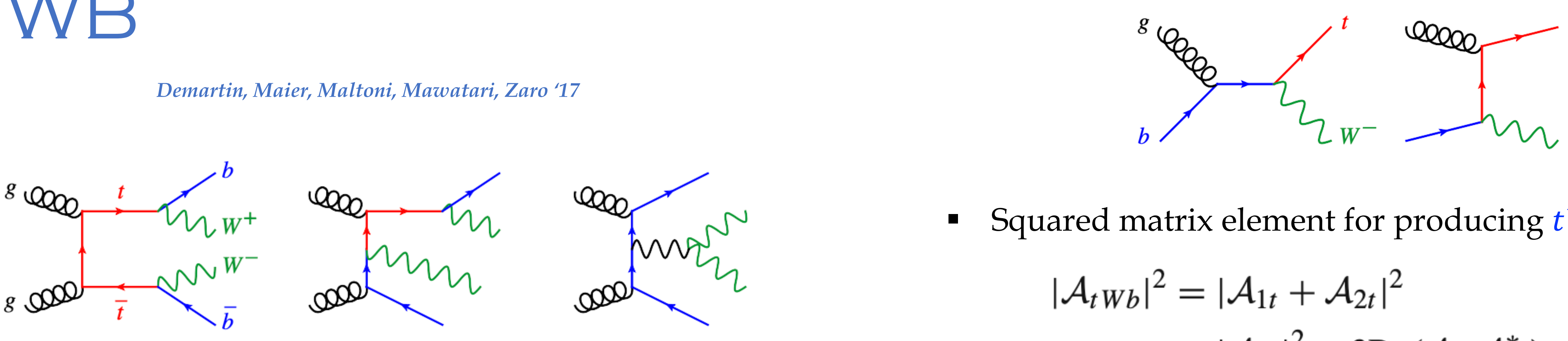
1

Backup

TWB

Demartin, Maier, Maltoni, Mawatari, Zaro '17



($\mathcal{A}_{2t}$) ($\mathcal{A}_{1t}$) ($\mathcal{A}_{0t}$)

- Squared matrix element for producing $tW^-\bar{b}$

$$|\mathcal{A}_{tWb}|^2 = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2$$
$$= |\mathcal{A}_{1t}|^2 + 2\mathrm{Re}(\mathcal{A}_{1t}\mathcal{A}_{2t}^*) + |\mathcal{A}_{2t}|^2,$$

- *DS (diagram subtraction):*

$$|\mathcal{A}_{tWb}|^2_{\mathrm{DS}} = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2 - \mathcal{C}_{2t},$$

- Local subtraction term C_{2t} by definition must cancel exactly the resonant matrix element $|\mathcal{A}_{2t}|^2$ when the kinematics is exactly on top of the resonant pole
- Gauge invariant
- Decrease quickly away from the resonant region

- *DR1 (without interference):*

$$|\mathcal{A}_{tWb}|^2_{\mathrm{DR1}} = |\mathcal{A}_{1t}|^2.$$

- *DR2 (with interference):*

$$|\mathcal{A}_{tWb}|^2_{\mathrm{DR2}} = |\mathcal{A}_{1t}|^2 + 2\mathrm{Re}(\mathcal{A}_{1t}\mathcal{A}_{2t}^*).$$

- DR schemes based on removing contributions all over the phase space
- They are not gauge invariant