The top-Higgs coupling at the LHC

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Motivation

The process

$$e^+e^- \rightarrow t\bar{t}h$$

is a sensitive probe of the top-Higgs Yukawa coupling g_{tth}.

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Fortunately, the top quarks are copiously produced at the LHC that, among others, allows for more and more precise determination of the top quark pair production cross section and for measurements of the cross sections of $t\bar{t}$ + jets.

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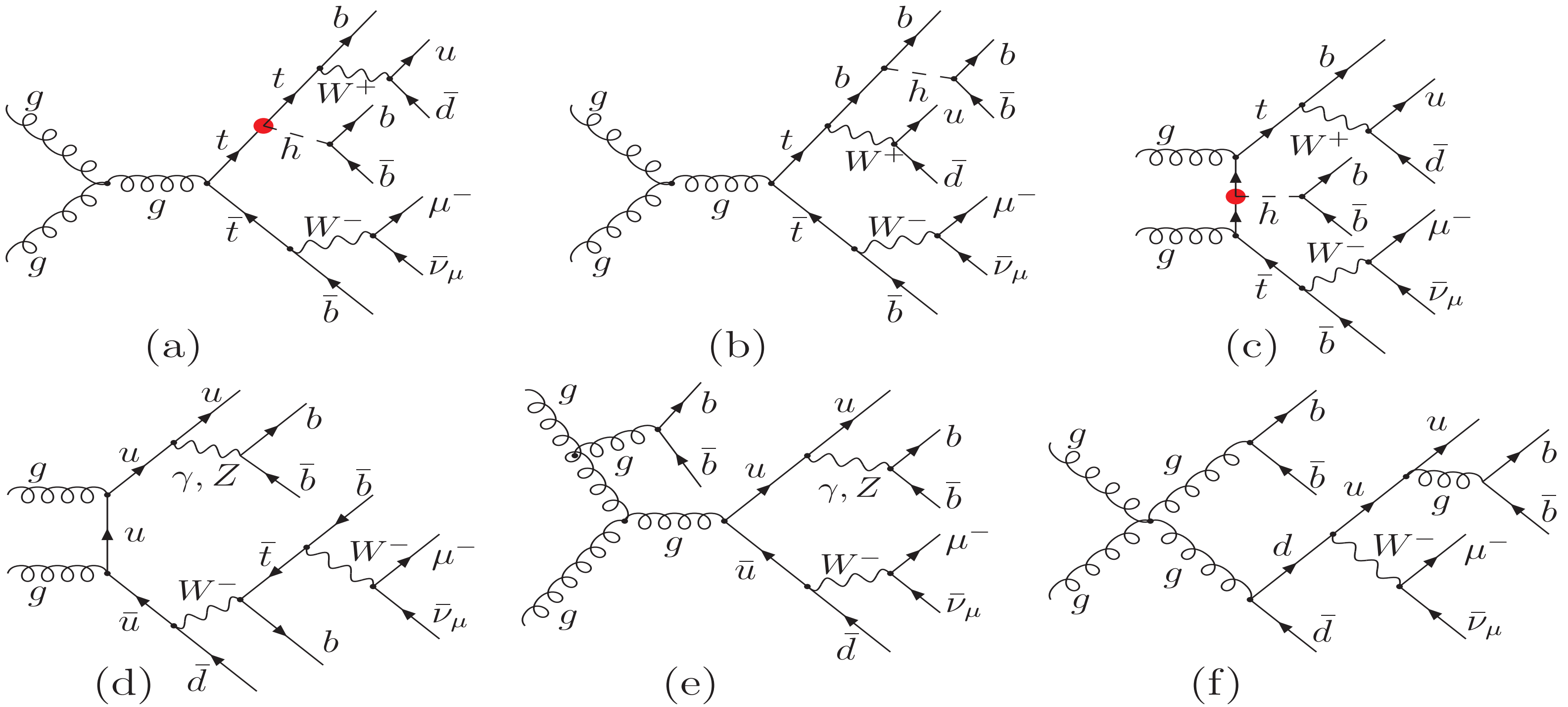
at the LHC is dominated by the gluon–gluon fusion mechanism. Taking into account decays: $h \to b\bar{b}$, $t \to bW^{+}$, $\bar{t} \to \bar{b}W^{-}$ and the subsequent decays of the W-bosons, we get hard scattering partonic processes such as

$$gg \;\to\; bu\bar{d}\bar{b}\mu^{-}\bar{\nu}_{\mu}b\bar{b}.$$

Feynman diagrams of $gg \to bu\bar{d}\bar{b}\mu^-\bar{\nu}_\mu b\bar{b}$



(a) (b) (c)

(d) (e) (f)

Red blobs indicate the top-Higgs coupling.

67 300 Feynman diagrams in the leading order of the SM, in the unitary gauge neglecting masses smaller than m_b and the CKM mixing, of which barely 56 diagrams constitute the signal of the $t\bar{t}h$ production.

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We will demonstrate how the background contributions obscure relatively clear effects of the anomalous $t\bar{t}h$ coupling in the signal cross section.

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We will demonstrate how the background contributions obscure relatively clear effects of the anomalous $t\bar{t}h$ coupling in the signal cross section.

Although the issue may seem somewhat premature from the experimental side, but in view of the excellent performance of the LHC, it may become relevant in quite a near future.

Lagrangian of $t\bar{t}h$ interaction

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The most general Lagrangian of $t\bar{t}h$ interaction including corrections from dimension-six operators that has been implemented in the program has the form

$$\mathcal{L}_{t\bar{t}h} = -g_{t\bar{t}h}\bar{t}\left(f + if'\gamma_5\right)th,$$

where $g_{t\bar{t}h} = m_t/v$, with $v = (\sqrt{2}G_F)^{-1/2} \simeq 246$ GeV, is the SM top-Higgs Yukawa coupling.

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Real couplings f and f' describe, respectively, scalar and pseudoscalar departures from the purely scalar top-Higgs Yukawa coupling of SM, reproduced for $f = 1$ and $f' = 0$.

Lagrangian of $t\bar{t}h$ interaction

Other dimension-six gauge-invariant effective operators are redundant, in a sense that they can be eliminated with the use of the equations of motion, both for the on- and off-shell particles.

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Obviously, the process may be affected by many other possible deviations from the SM couplings that are not considered here, as our goal is to illustrate just the effects of the anomalous $t\bar{t}h$ interaction on the distributions of the secondary lepton.

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Obviously, the process may be affected by many other possible deviations from the SM couplings that are not considered here, as our goal is to illustrate just the effects of the anomalous $t\bar{t}h$ interaction on the distributions of the secondary lepton.

However, some deviations, e.g., the anomalous Wtb coupling can be easily included, as it has been already implemented in `carlomat`.

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Indirect constraints of the $t\bar{t}h$ interaction vertex can be derived from measurements of the Higgs boson production rate through the gluon-gluon fusion process, which is dominated by a top-quark loop, and of the Higgs boson decay into 2 photons that, despite being dominated by the W boson loop, also receives a significant contribution from the top-quark loop.

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However, extraction of the $t\bar{t}h$ coupling in this way relies on the assumption that the loops do not receive contributions from new massive fundamental particles beyond those of the SM.

Experimental constraints on f and f'

If two universal scale factors C_f and C_V are assumed, for the Higgs boson Yukawa couplings to all the SM fermion species

$$g_{hf\bar{f}} = C_f \frac{m_f}{v}$$

and for the Higgs boson couplings to the EW gauge bosons

$$g_{hVV} = C_V g_{hVV}^{SM}, \quad V = W, Z,$$

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$$g_{hVV} = C_V g^{SM}_{hVV}, \quad V = W, Z,$$

and if there is no new physical degrees of freedom, then the scalar coupling f can be constraint at 95% C.L. to be in the regions:

$$f \in [-1.2, -0.6] \cup [0.6, 1.3] \qquad \text{ATLAS}$$

$$f \in [0.3, 1.0] \qquad \text{CMS.}$$

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The relative sign of both couplings could probably be best determined in the reaction of associated production of the single top quark and Higgs boson in proton-proton collisions at the LHC through the underlying t-channel partonic process $qb \to tq'h$.

Calculation details

The on-shell poles in propagators of unstable particles, both the *s*- and *t*-channel ones, are avoided by making the substitutions:

$$\begin{aligned} m_B^2 &\to M_B^2 = m_B^2 - i m_B \Gamma_B, \quad B = Z, W, h, \\ m_t &\to M_t = \sqrt{m_t^2 - i m_t \Gamma_t}\,, \end{aligned}$$

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but has no field theoretical justification in the t-channel propagators.

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Unitarity violation effects at high energies caused by the resummation are minimized if the computation is performed in the complex mass scheme, i.e., with the complex EW mixing parameter

$$\sin^2\theta_W = 1 - M_W^2/M_Z^2$$

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Note, that the electric charge e_W can be defined as a real quantity:

$$e_W = \sqrt{4\pi\alpha_W}, \qquad \text{with} \qquad \alpha_W = \frac{\sqrt{2}G_F m_W^2}{\pi}\left(1 - \frac{m_W^2}{m_Z^2}\right),$$

as it enters all the EW couplings multiplicatively, thus the only effect of using the complex masses would be the overall change of normalization of the cross section.

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i.e., it is a complex quantity, as it is parametrized in terms of the complex masses and complex EW mixing parameter $\sin\theta_W$.

Event selection cuts

Jets are identified with their original partons and the following cuts are imposed to select events with separate jets, an isolated charged lepton and missing transverse momentum:

$$p_{Tl} > 30\ \mathrm{GeV}, \quad p_{Tj} > 30\ \mathrm{GeV}, \quad |\eta_l| < 2.1, \quad |\eta_j| < 2.4,$$

$$\not{E}^T > 20\ \mathrm{GeV}, \qquad \Delta R_{lj,jj} = \sqrt{(\eta_i - \eta_k)^2 + (\varphi_i - \varphi_k)^2} > 0.4,$$

where the subscripts l and j stand for *lepton* and *jet*.

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100% efficiency of b tagging is assumed.

Cuts on invariant masses

of two non b jets, $b_{\sim b_1}$ and $b_{\sim b_2}$,

$$60\ \mathrm{GeV} < \left[(p_{\sim b_1} + p_{\sim b_2})^2\right]^{1/2} < 90\ \mathrm{GeV},$$

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on the transverse mass of the muon–neutrino system

$$\left[m_\mu^2 + 2\left(m_\mu^2 + |\vec{p}_\mu^{\,T}|^2\right)^{1/2} |\vec{\not{p}}^{\,T}| - 2\vec{p}_\mu^{\,T} \cdot \vec{\not{p}}^{\,T}\right]^{1/2} < 90\ \text{GeV},$$

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of a b jet, b_1, and the two non b jets

$$\left|\left[\left(p_{b_1} + p_{\sim b_1} + p_{\sim b_2}\right)^2\right]^{1/2} - m_t\right| < 30\ \mathrm{GeV},$$

Cuts on invariant masses

the transverse mass m_T of a b quark, b_2, muon and missing transverse energy

$$m_t - 30\ \text{GeV} < m_T < m_t + 10\ \text{GeV}$$

where

$$m_T^2 = m^2 + 2\left(m^2 + \left|\vec{p}_{b_2}^{\,T} + \vec{p}_{\mu}^{\,T}\right|^2\right)^{1/2} \not{E}^T - 2\left(\vec{p}_{b_2}^{\,T} + \vec{p}_{\mu}^{\,T}\right) \cdot \vec{\not{p}}^{\,T},$$

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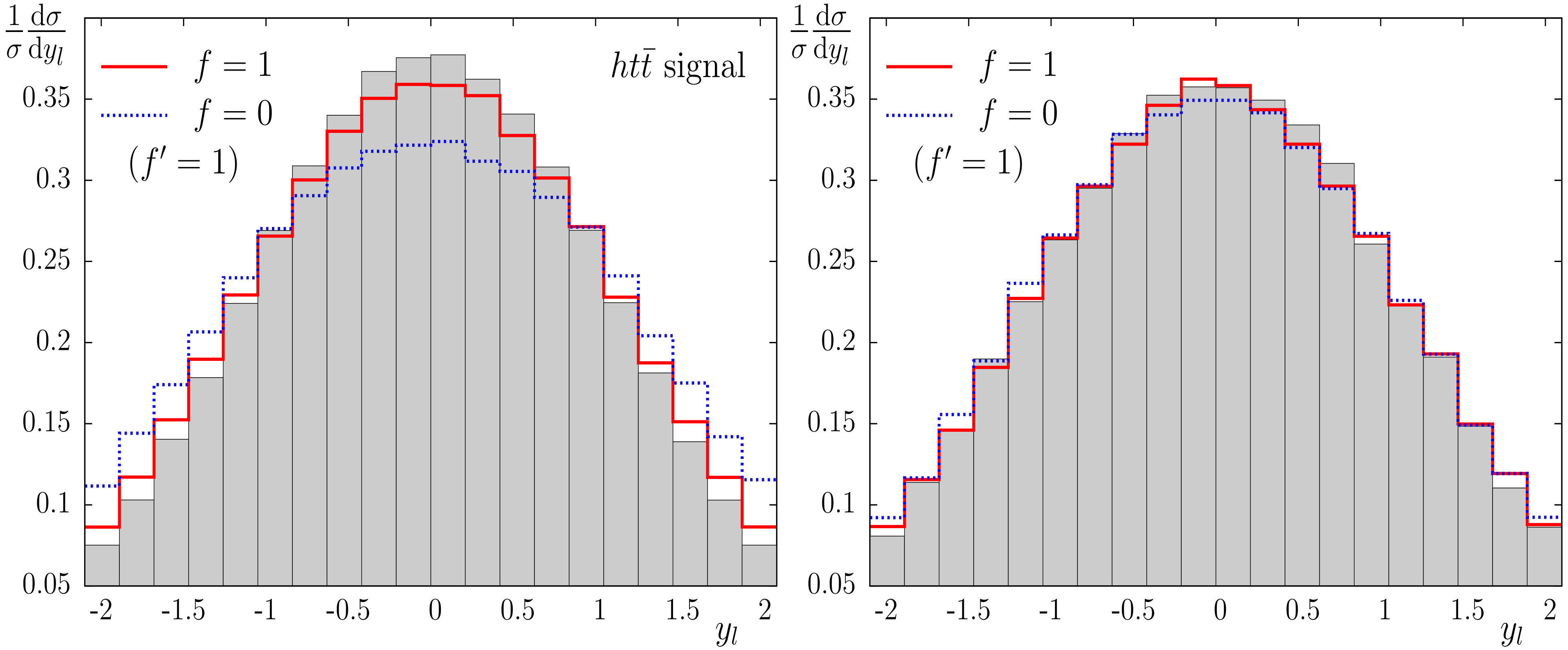
with $m^2 = \left(p_{b_2} + p_\mu\right)^2$,

the invariant mass cut on two b jets, b_3 and b_4,

$$\left|\left[\left(p_{b_3} + p_{b_4}\right)^2\right]^{1/2} - m_h\right| < 20\ \mathrm{GeV}.$$

$pp \to b\bar{b}bu\bar{d}\bar{b}\mu^-\bar{\nu}_\mu$ at $\sqrt{s} = 14$ TeV

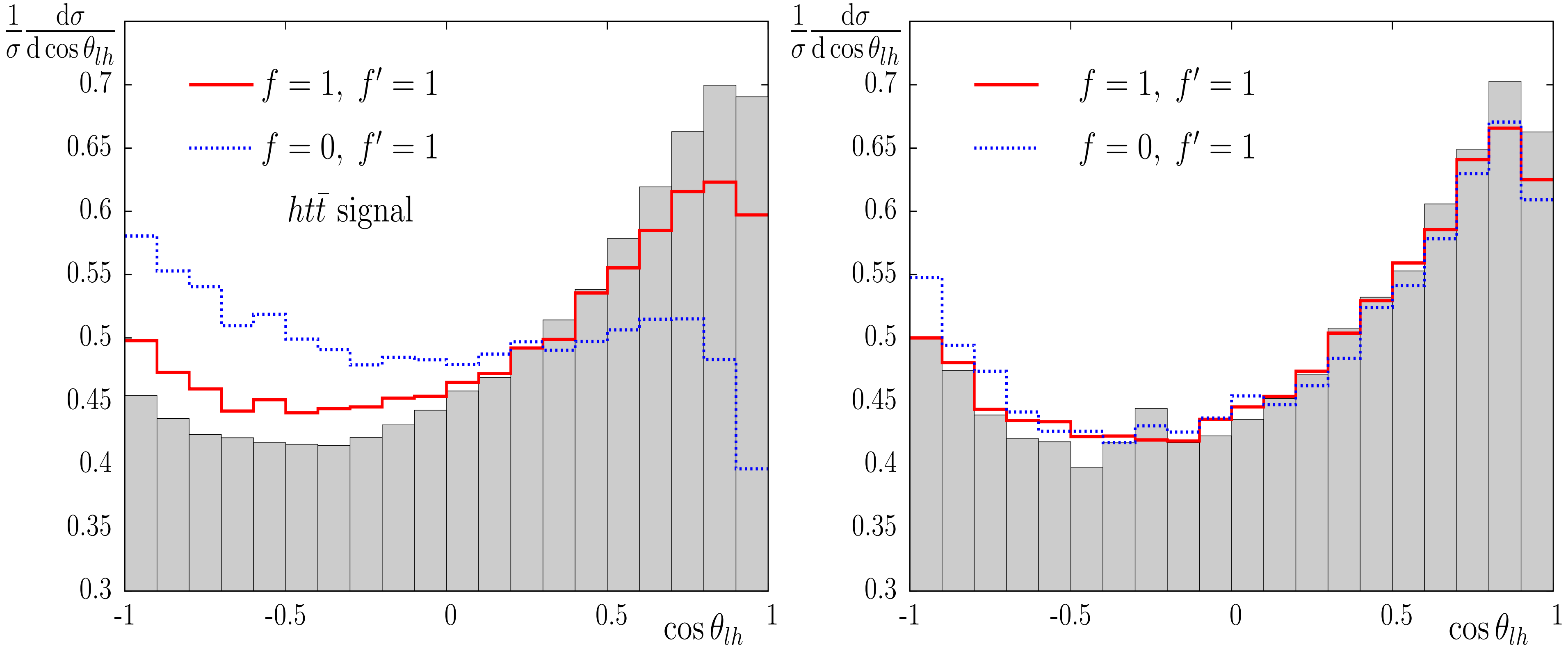
Rapidity distributions of μ^- with signal (left) and all (right) Feynman diagrams (CTEQ6L PDFs with $Q = 2m_t + m_h$):



From K. Kołodziej, JHEP **07** (2013) 083.

$pp \to b\bar{b}bu\bar{d}\bar{b}\mu^-\bar{\nu}_\mu$ at $\sqrt{s} = 14$ TeV

Distributions in cosine of the μ^--Higgs boson angle with signal (left) and all (right) Feynman diagrams (CTEQ6L PDFs with $Q = 2m_t + m_h$):



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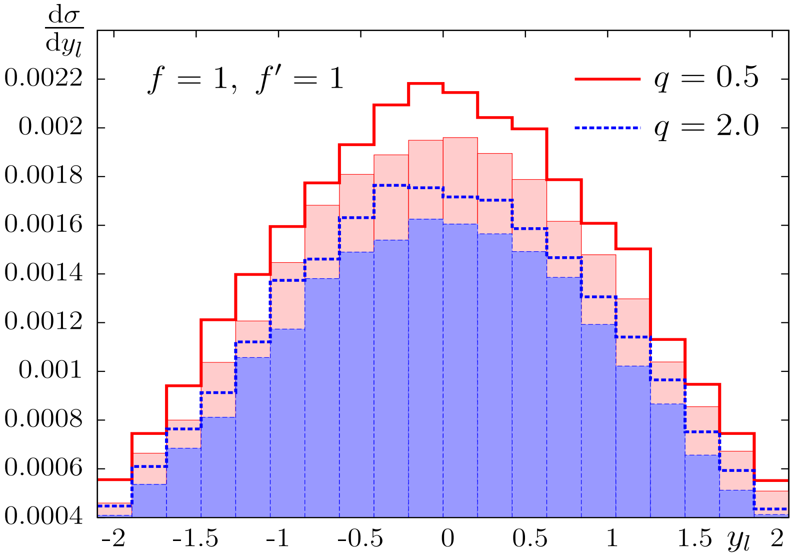

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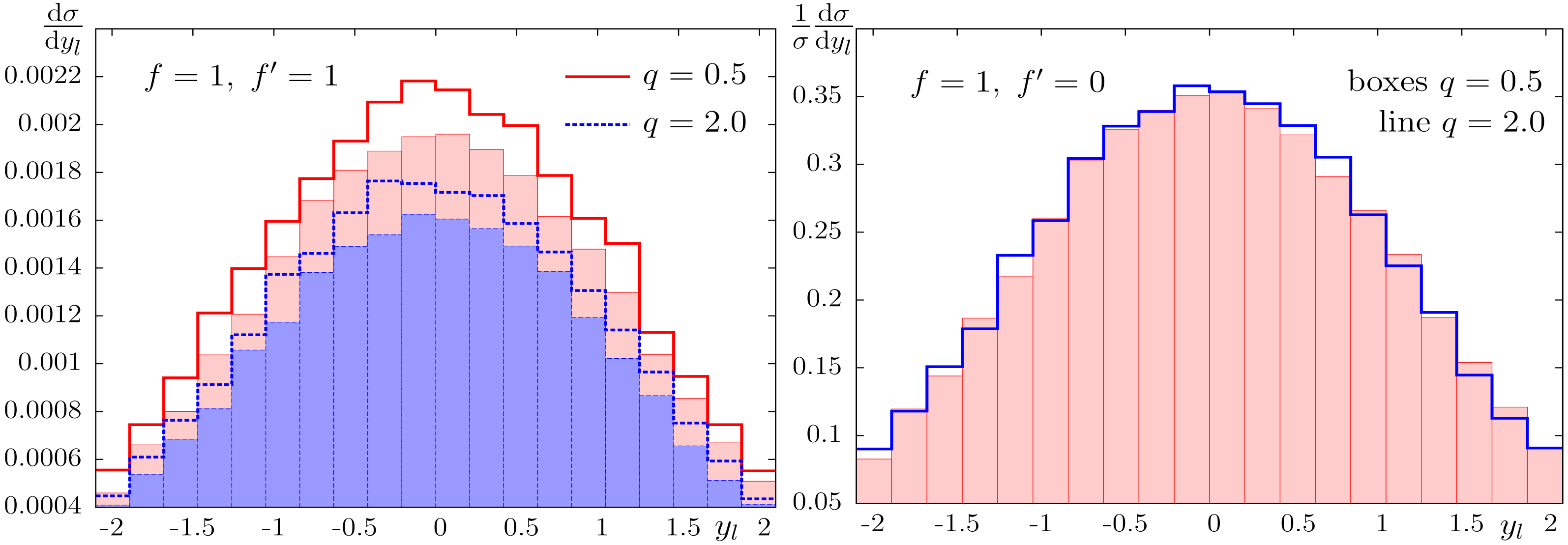

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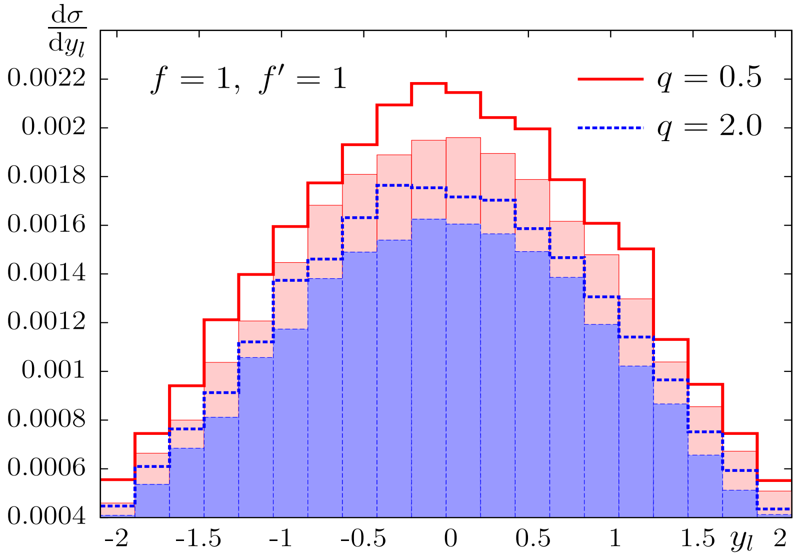

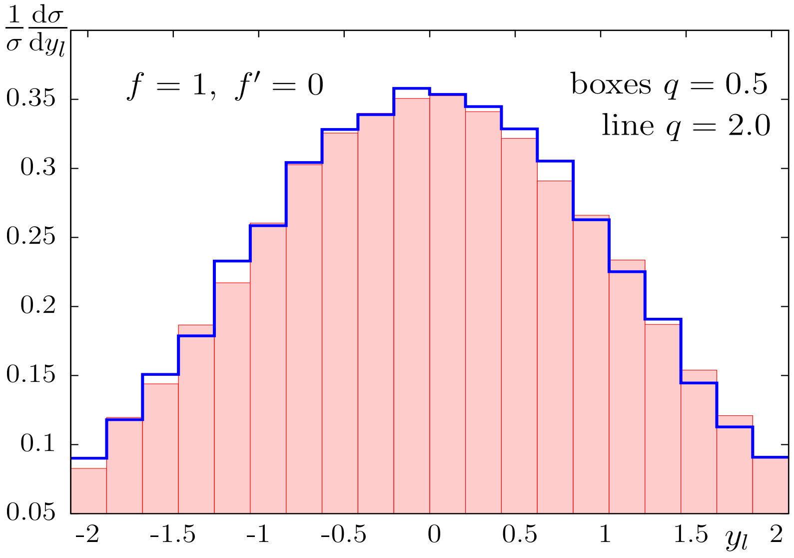

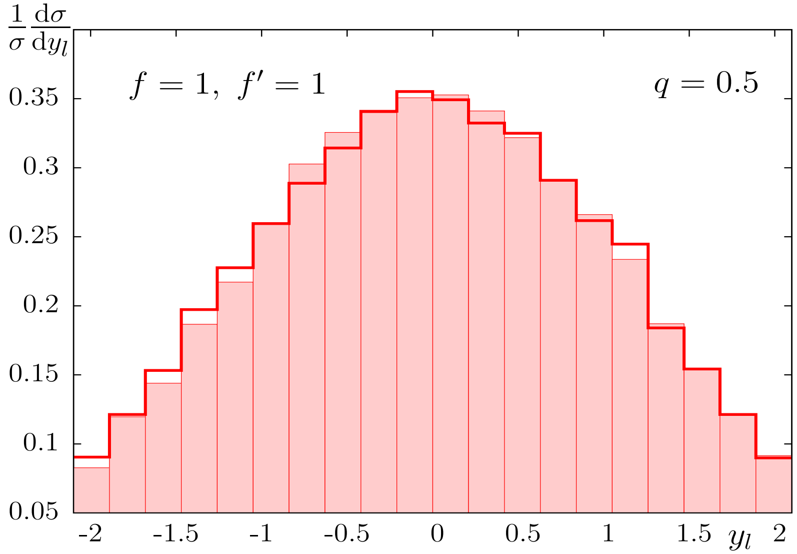

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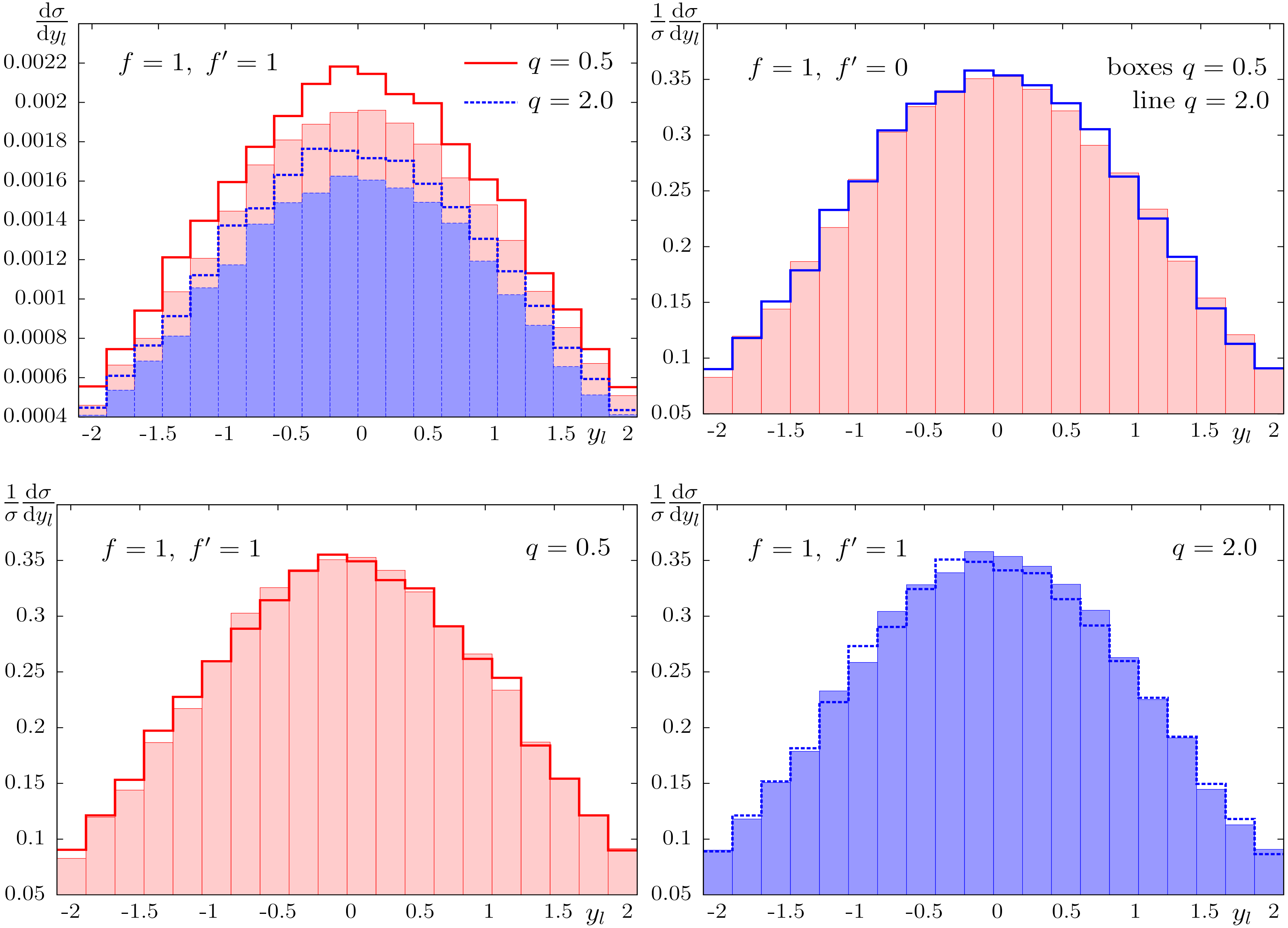

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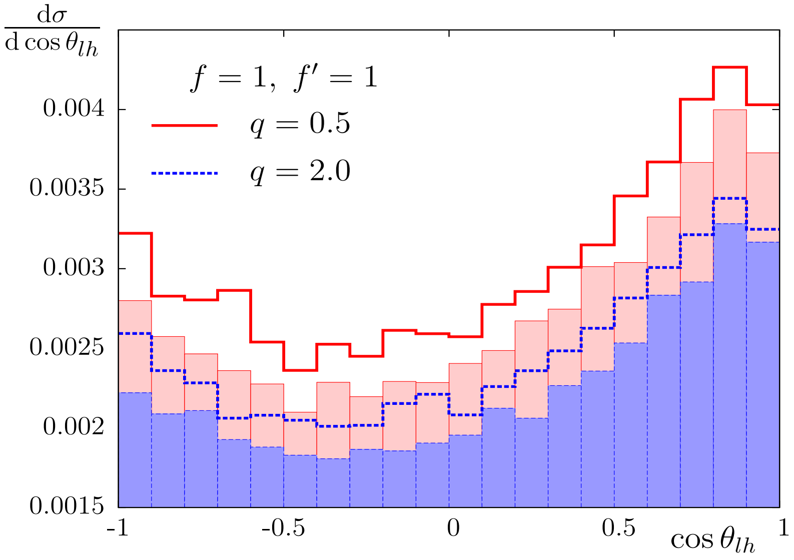

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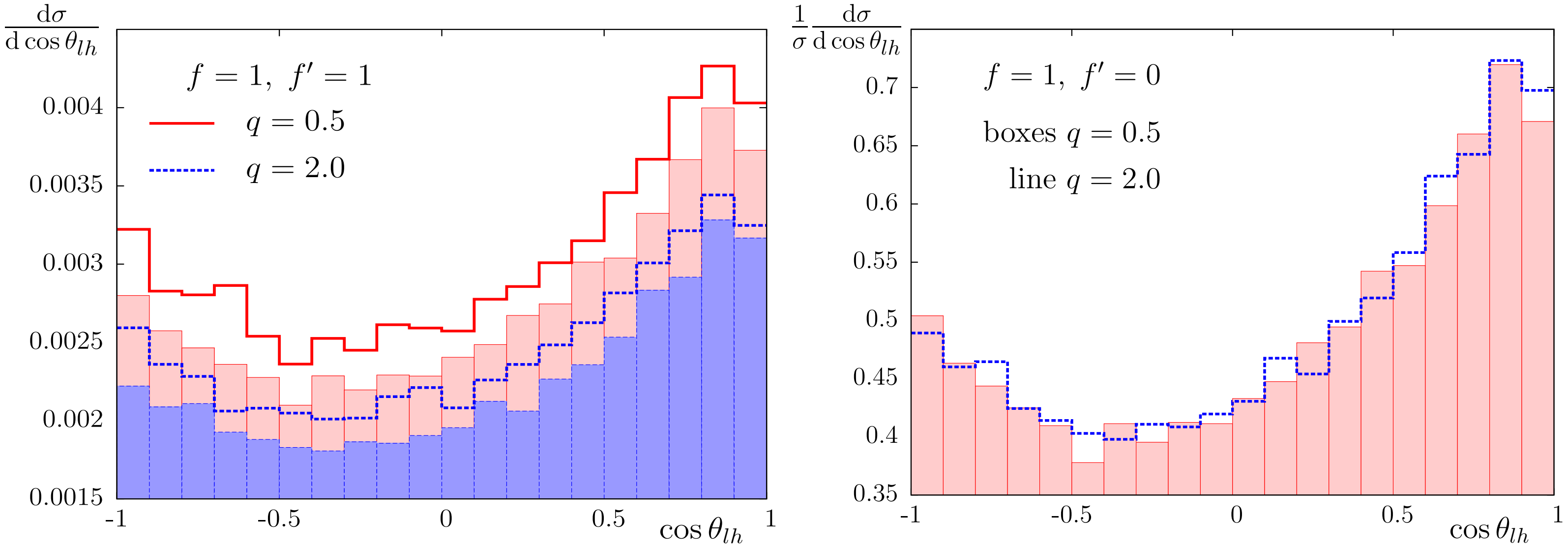

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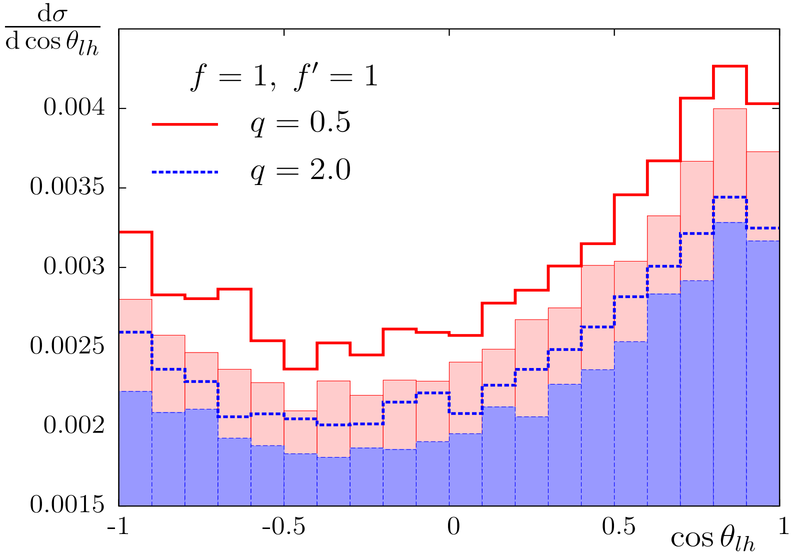

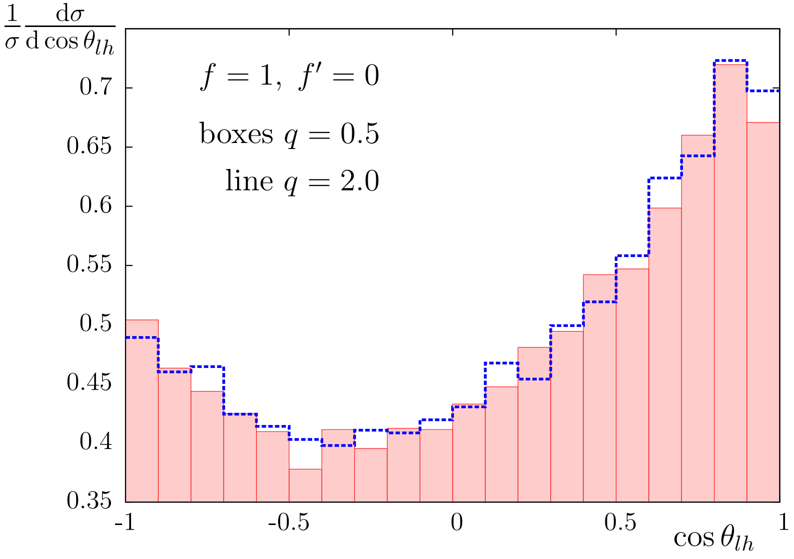

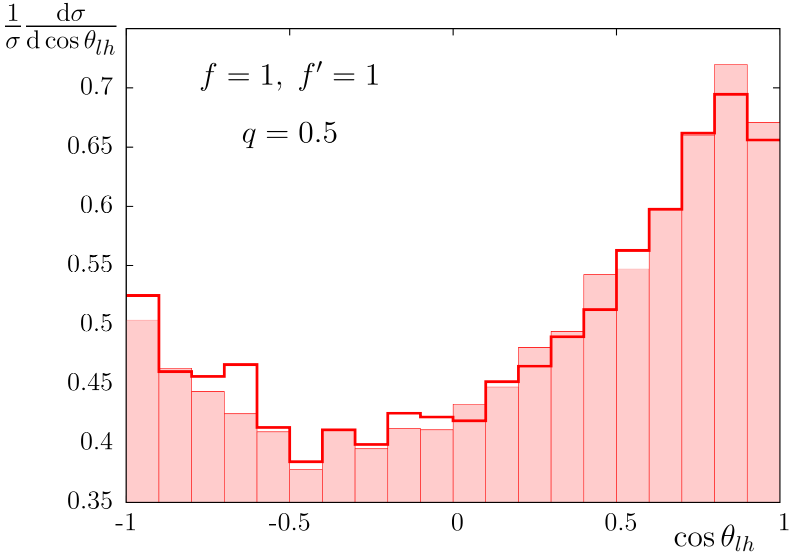

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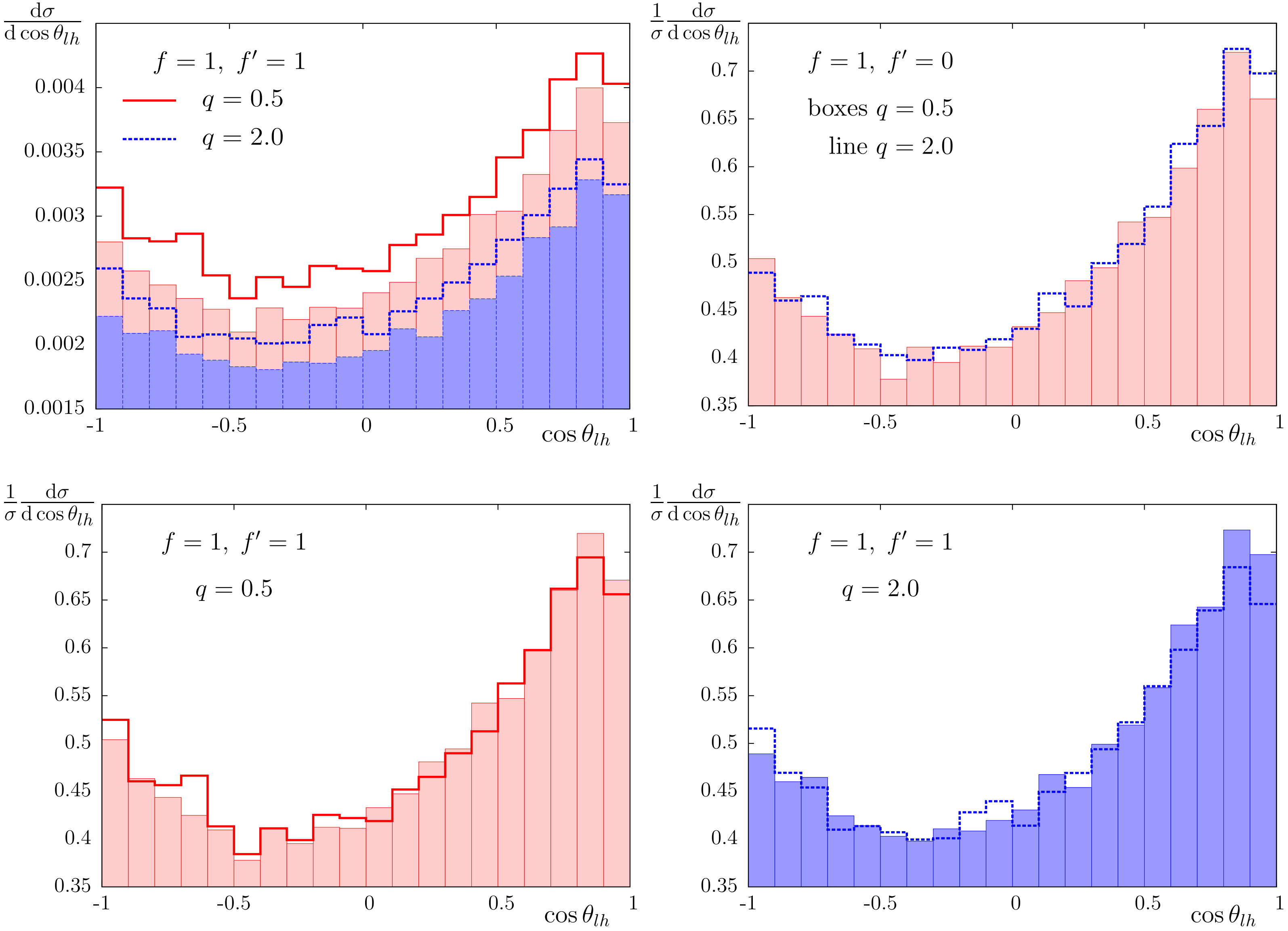

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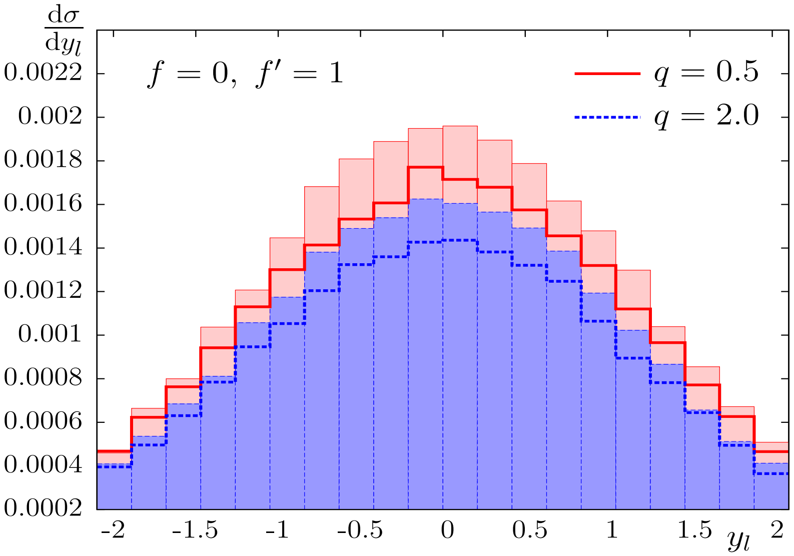

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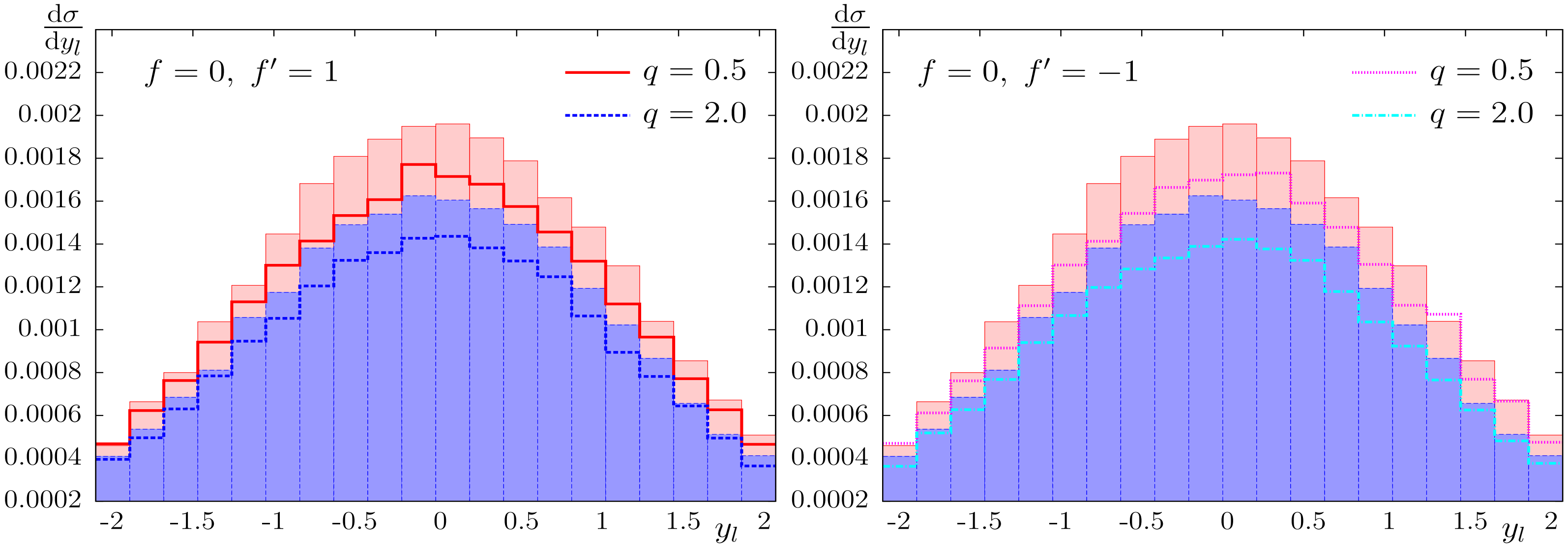
Rapidity distributions of μ^- (MSTW LO PDFs with $Q = q(2m_t + m_h)$):



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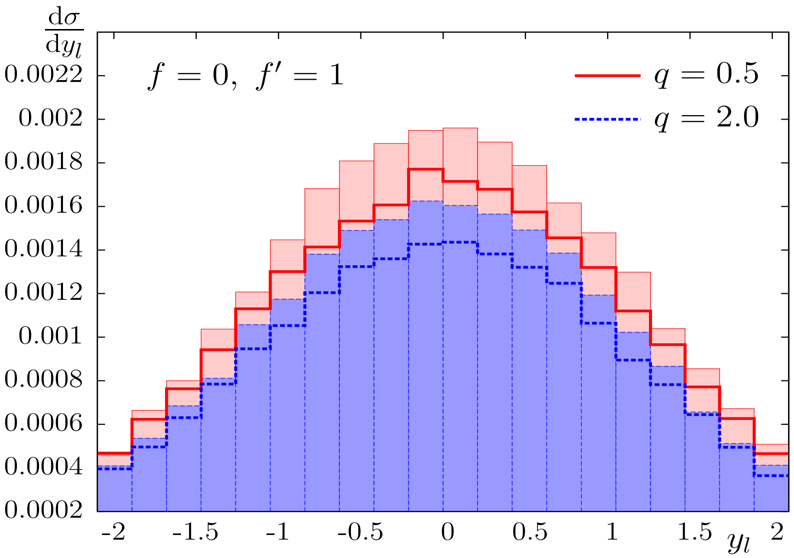

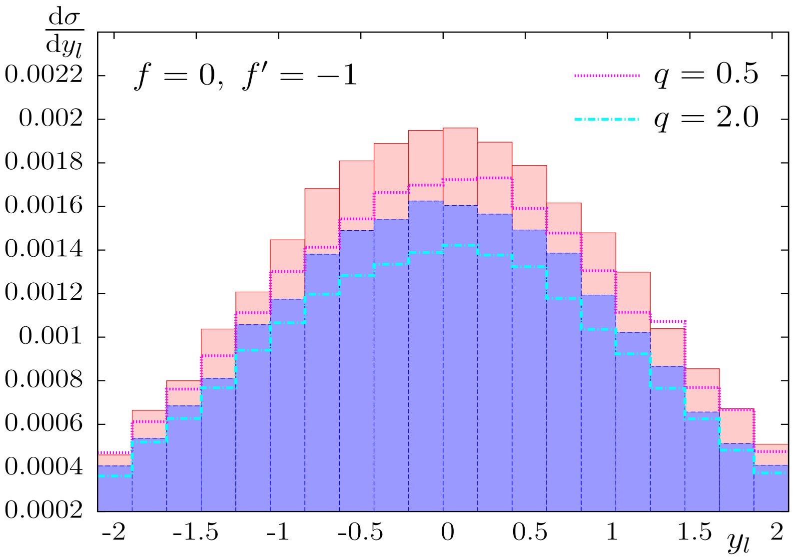

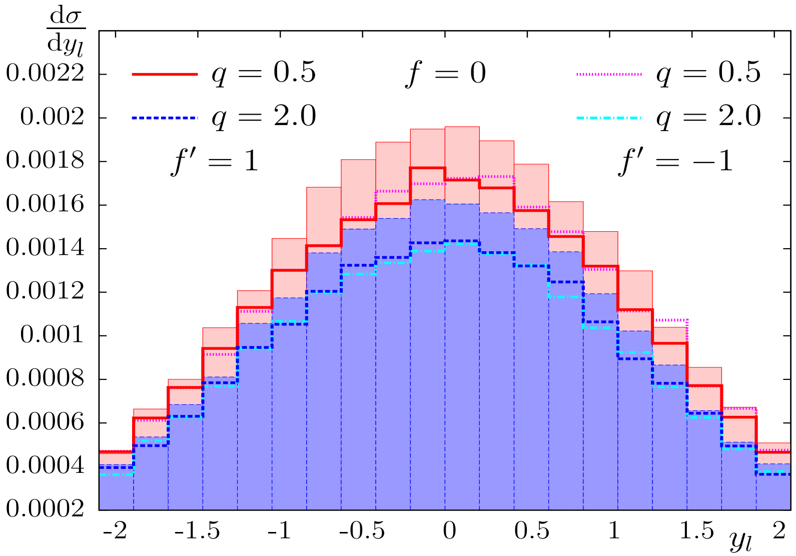

Little dependence on the sign of f'.

$pp \rightarrow b\bar{b}bu\bar{d}\bar{b}\mu^-\bar{\nu}_\mu$ at $\sqrt{s} = 14$ TeV

The signal significance $\mu = \sigma(f, f')/\sigma_{SM}$ and differences in expected numbers of events, $\Delta n = n(f, f') - n_{SM}$:
($L = 100$ fb^{-1}, 100% detection efficiency)

	$m_{b\bar{b}} < 20$ GeV				$m_{b\bar{b}} < 10$ GeV			
	$\cos\theta_{lh} < 0$		$\cos\theta_{lh} > 0$		$\cos\theta_{lh} < 0$		$\cos\theta_{lh} > 0$	
(f, f')	μ	Δn	μ	Δn	μ	Δn	μ	Δn
$(0, 1)$	0.90	−148	0.83	−265	0.85	−174	0.78	−275
$(0, -1)$	0.90	−151	0.84	−252	0.84	−188	0.78	−270
$(1, 1)$	1.20	295	1.17	251	1.23	261	1.17	210
$(1, -1)$	1.20	302	1.15	238	1.24	279	1.18	221

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$$\mu = \begin{cases} 1.6 & \text{for} \quad \cos\theta_{lh} < 0, \\ 1.4 & \text{for} \quad \cos\theta_{lh} > 0, \end{cases}$$

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Tighter cuts should be imposed to suppress the off resonance background.

Summary and conclusions

The most general Lagrangian of $t\bar{t}h$ interaction including corrections from dimension-six operators has been implemented in `carlomat`.

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The final state lepton distributions in the process of associated production of the Higgs boson and top quark pair are sensitive to possible modifications of the SM top-Higgs coupling.

In particular the distributions in the lepton rapidity and cosine of the lepton angle with respect to the reconstructed Higgs boson momentum computed with the $t\bar{t}h$ signal diagrams only are substantially changed.

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Thank you for your attention