Irreducible background and interference effects for Higgs-boson production in association with a top-quark pair

JHEP **1504** (2015) 008 [arXiv:1412.5290]

Robert Feger
University of Würzburg

in collaboration with
Ansgar Denner and Andreas Scharf (University of Würzburg)

LHC Higgs XS ttH (Theory Update)
Würzburg/CERN, 9.6.2015

Introduction

Three scenarios

$t\bar{t}H$ production $\quad pp \to t\bar{t}H \to l^+\nu_l jjb\bar{b}b\bar{b}$

$t\bar{t}b\bar{b}$ production $\quad pp \to t\bar{t}b\bar{b} \to l^+\nu_l jjb\bar{b}b\bar{b}$

full Process $\quad pp \to l^+\nu_l jjb\bar{b}b\bar{b}$

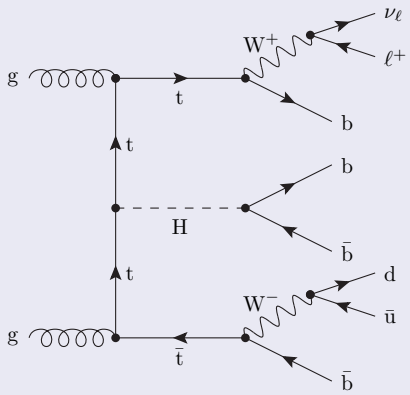
Leading-order analysis of $pp \to t\bar{t}H \to l^+\nu_l jjb\bar{b}b\bar{b}$

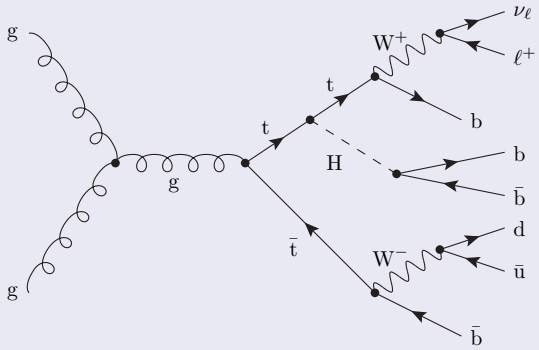
- **determine irreducible background** by comparison of the three scenarios
- **investigate interference effects from different coupling orders** by comparing results including all orders and interference effects with a sum of fixed order results
- **study methods of assigning a b-jet pair to Higgs-boson decay**:
  4 b jets in final state $\Rightarrow$ 6 b-jet pair combinations
  consider combination of the two b jets
  - forming the invariant mass closest to the Higgs-boson mass,
  - most likely not originating from (anti-)top-quark decay,
  - having the smallest ΔR distance.

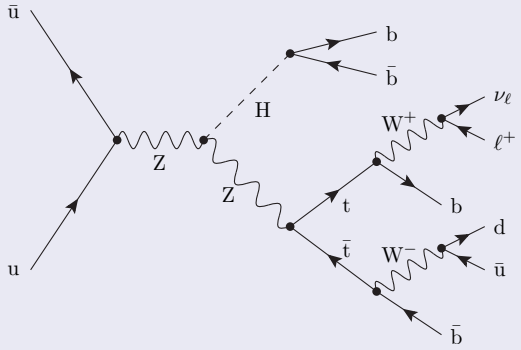
Process $pp \to t\bar{t}H \to l^+\nu_l jjb\bar{b}b\bar{b}$

Scenario 1: $t\bar{t}H$ production ($pp \to t\bar{t}H \to l^+\nu_l jjb\bar{b}b\bar{b}$)

- intermediate t, $\bar{t}$, H required
  treated in pole approximation
- gluon-gluon partonic channels $gg \to l^+\nu_l q'\bar{q}''b\bar{b}b\bar{b}$
  order of amplitude: $\mathcal{O}(\alpha_s\alpha^3)$
  quark–antiquark partonic channels $q\bar{q} \to l^+\nu_l q'\bar{q}''b\bar{b}b\bar{b}$
  order of amplitude: $\mathcal{O}(\alpha_s\alpha^3)$, $\mathcal{O}(\alpha^4)$
- sample diagrams



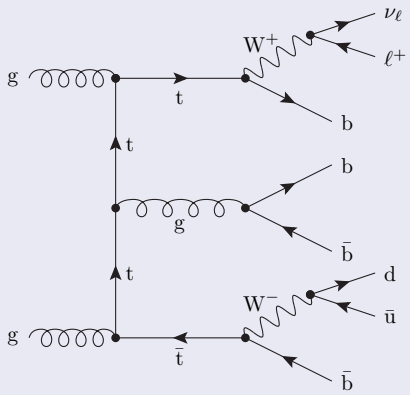


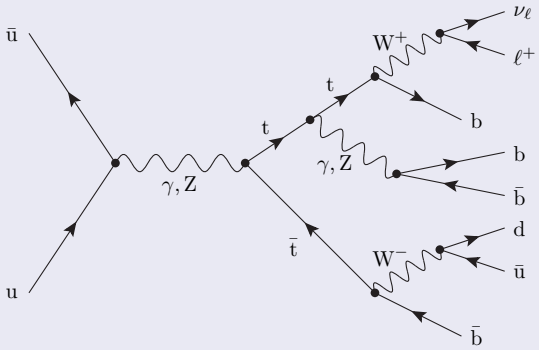


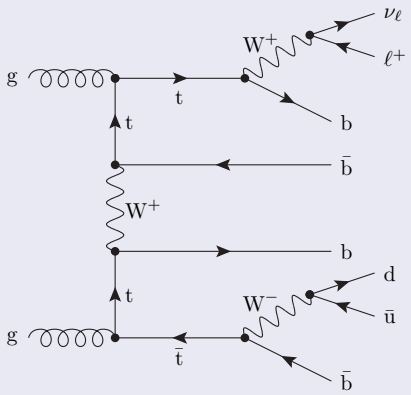
Process $pp \to t\bar{t}b\bar{b} \to l^+\nu_l jjb\bar{b}b\bar{b}$

Scenario 3: $t\bar{t}b\bar{b}$ production ($pp \to t\bar{t}b\bar{b} \to l^+\nu_l jjb\bar{b}b\bar{b}$)

- intermediate t, $\bar{t}$ required, treated in pole approximation
  no resonant Higgs required
- same partonic channels as above
  additional $\mathcal{O}(\alpha_s^2\alpha^2)$ contributions for gg and $q\bar{q}'$ channels
- sample diagrams



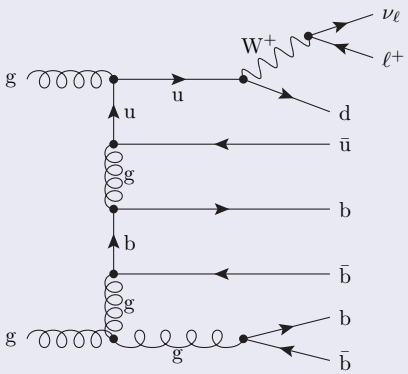


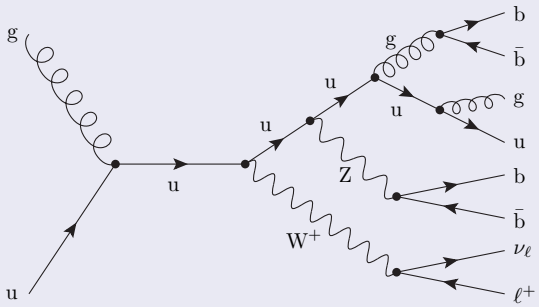


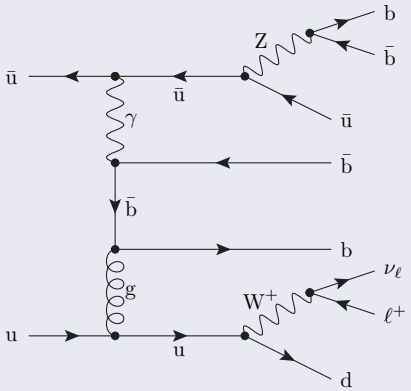
Process $pp \to l^+\nu_l jjb\bar{b}b\bar{b}$

Scenario 3: full Process ($pp \to l^+\nu_l jjb\bar{b}b\bar{b}$)

- no resonances required
- number of channels increases by more than factor 4 owing to crossing symmetric channels
- amplitude receives contributions of $\mathcal{O}(\alpha^4)$, $\mathcal{O}(\alpha_s\alpha^3)$, $\mathcal{O}(\alpha_s^2\alpha^2)$ and $\mathcal{O}(\alpha_s^3\alpha)$ with up to 78052 diagrams for individual channels! (unitary gauge)
- sample diagrams







Calculational setup

Setup

- complex-mass scheme for unstable particles Denner, Dittmaier, Roth, Wieders '99
- on-shell projection for resonances treated in pole approximation such that invariants of other resonances are not shifted!
- massless light quarks, massive b-quarks
- only PDFs of light quarks included (u, d, c, s) besides gluons
- all matrix elements calculated with RECOLA (recursive algorithm) Actis et al.
- phase-space integration: multi-channel Monte Carlo
  $\Rightarrow$ number of diagrams matters

Scale Choice and PDFs

- pp collider energy: 13 TeV
- scale choice: Beenakker et al. '03

$$\mu = \mu_R = \mu_F = \frac{1}{2}(2m_t + m_H) = 236\,\text{GeV} \quad (1)$$

- PDFs: CT10LO Lai et al. '10

Setup for numerics

Input parameters

$$
\begin{aligned}
m_t &= 173\,\text{GeV}, & \Gamma_t &= 1.47\,\text{GeV},\\
M_H &= 126\,\text{GeV}, & \Gamma_H &= 4.21\times10^{-3}\,\text{GeV},\\
M_Z^{OS} &= 91.1876\,\text{GeV}, & \Gamma_Z^{OS} &= 2.4952\,\text{GeV},\\
M_W^{OS} &= 80.385\,\text{GeV}, & \Gamma_W^{OS} &= 2.0850\,\text{GeV},\\
m_b &= 4.8\,\text{GeV}
\end{aligned}
\tag{2}
$$

Cuts

$$
\begin{aligned}
&\text{non-b jets:} && p_{T,j} > 25\,\text{GeV}, && |y_j| < 2.5, && \Delta R_{jj} > 0.4,\\
&\text{b jets:} && p_{T,b} > 25\,\text{GeV}, && |y_b| < 2.5, && \Delta R_{bb} > 0.4, \quad \Delta R_{jb} > 0.4\\
&\text{charged lepton:} && p_{T,l^+} > 20\,\text{GeV}, && |y_{l^+}| < 2.5,\\
&\text{missing } p_T\text{:} && p_{T,\text{miss}} > 20\,\text{GeV}
\end{aligned}
\tag{3}
$$

Identifying b-jet pairs from Higgs decay

Best unbiased method: b quarks originating from $t\bar{t}$ are selected according to

$$
\mathcal{L} \propto \frac{1}{\left(p^2_{l^+\nu_l b_i} - m_t^2\right)^2 + \left(m_t\Gamma_t\right)^2} \, \frac{1}{\left(p^2_{j_1 j_2 b_j} - m_t^2\right)^2 + \left(m_t\Gamma_t\right)^2}
\tag{4}
$$

Total cross section for $pp \to t\bar{t}H \to l^+\nu_l jjb\bar{b}b\bar{b}$

Total cross section for $pp \to t\bar{t}H \to l^+\nu_l jjb\bar{b}b\bar{b}$

pp	Cross section [fb] $\mathcal{O}((\alpha^4)^2)$	$\mathcal{O}((\alpha_s\alpha^3)^2)$	Total
$q\bar{q}$	0.014887(2)	2.1467(2)	2.1621(2)
gg	–	5.230(1)	5.2298(9)
$\sum$	0.014887(2)	7.377(1)	7.3920(9)

Discussion

- 70% from gg processes
- $\mathcal{O}((\alpha_s\alpha^3)^2)$ dominates
- pure EW contribution tiny
- no interferences between different orders

Total cross section for $pp \to t\bar{t}b\bar{b} \to l^+\nu_l jjb\bar{b}b\bar{b}$

Total cross section for $pp \to t\bar{t}b\bar{b} \to l^+\nu_l jjb\bar{b}b\bar{b}$

pp	Cross section [fb] $\mathcal{O}((\alpha^4)^2)$	$\mathcal{O}((\alpha_s\alpha^3)^2)$	$\mathcal{O}((\alpha_s^2\alpha^2)^2)$	Sum	Total	Interference
$q\bar{q}$	0.018134(6)	2.4932(9)	0.9199(2)	3.4312(9)	3.4366(6)	$< +1\,\%$
gg	–	7.818(4)	16.650(9)	24.47(1)	23.010(7)	$\sim -6\,\%$
$\sum$	0.018134(6)	10.311(4)	17.570(9)	27.90(1)	26.446(7)	$\sim -5\,\%$

Irreducible background

Irreducible background from $t\bar{t}b\bar{b}$:

$$\sigma_{t\bar{t}b\bar{b}}^{\text{Irred.}} = \sigma_{t\bar{t}b\bar{b}}^{\text{Total}} - \sigma_{t\bar{t}H}^{\text{Total}} = 19.06\,\text{fb} \quad (260\%) \tag{5}$$

mainly from QCD production (Higgs replaced by gluon)
additional background from Z bosons, W bosons and photons

Total cross section for $pp \to t\bar{t}b\bar{b} \to l^+\nu_l jjb\bar{b}b\bar{b}$

Total cross section for $pp \to t\bar{t}b\bar{b} \to l^+\nu_l jjb\bar{b}b\bar{b}$

pp	Cross section [fb] $\mathcal{O}((\alpha^4)^2)$	$\mathcal{O}((\alpha_s\alpha^3)^2)$	$\mathcal{O}((\alpha_s^2\alpha^2)^2)$	Sum	Total	Interference
$q\bar{q}$	0.018134(6)	2.4932(9)	0.9199(2)	3.4312(9)	3.4366(6)	$< +1\,\%$
gg	–	7.818(4)	16.650(9)	24.47(1)	23.010(7)	$\sim -6\,\%$
$\sum$	0.018134(6)	10.311(4)	17.570(9)	27.90(1)	26.446(7)	$\sim -5\,\%$

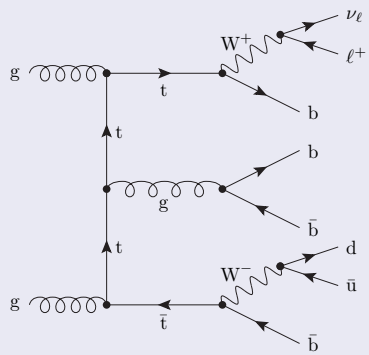
Interferences between different orders

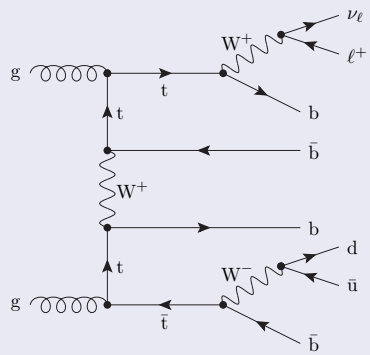
-6% in gg channels, -5% for $\sigma_{t\bar{t}b\bar{b}}$

main source:

interferences of dominant QCD diagrams with t-channel W-exchange diagrams

signal–background interference $< 1\%$





Total cross section for $pp \to l^+\nu_l jjb\bar{b}b\bar{b}$

Total cross section for $pp \to l^+\nu_l jjb\bar{b}b\bar{b}$

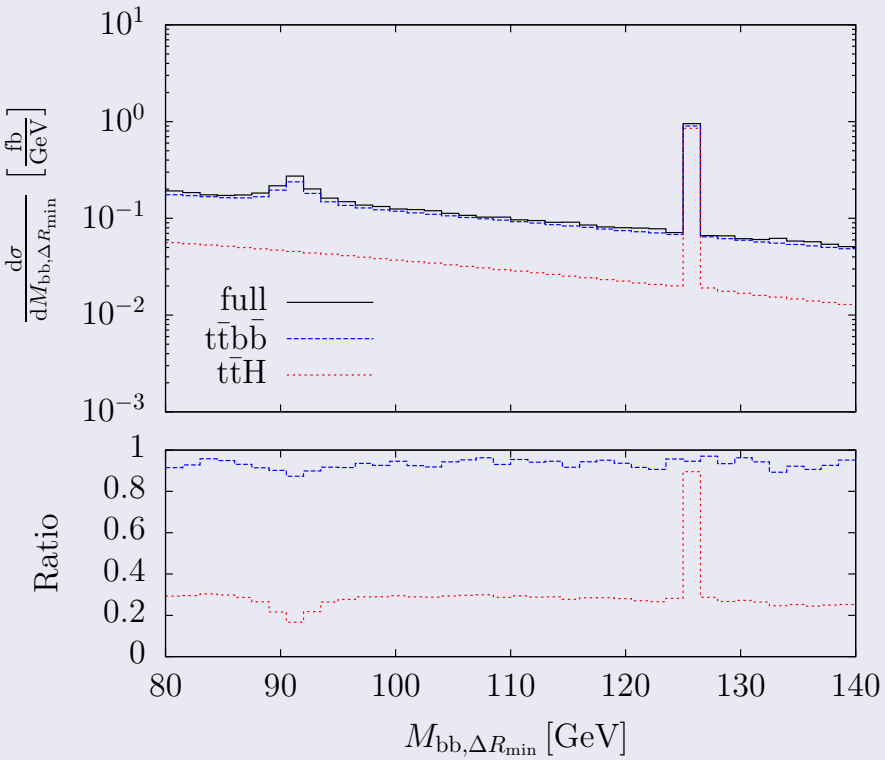
pp	Cross section [fb] $\mathcal{O}((\alpha^4)^2)$	$\mathcal{O}((\alpha_s\alpha^3)^2)$	$\mathcal{O}((\alpha_s^2\alpha^2)^2)$	$\mathcal{O}((\alpha_s^3\alpha)^2)$	Sum	Total
gq	–	0.231(4)	0.370(2)	0.365(1)	0.966(4)	0.944(9)
$g\bar{q}$	–	0.0421(6)	0.0679(3)	0.0608(2)	0.1708(7)	0.167(1)
$qq^{(\prime)}$	0.001471(2)	0.0575(5)	0.1106(2)	0.07871(9)	0.2483(6)	0.2478(8)
$q\bar{q}$	0.01973(3)	2.531(6)	0.957(1)	0.00333(1)	3.511(6)	3.538(4)
gg	–	8.01(2)	17.19(6)	0.00756(2)	25.21(6)	23.71(6)
$\sum$	0.02120(3)	10.87(2)	18.69(6)	0.516(2)	30.10(6)	28.60(6)

Discussion

- 83% from gg processes
- additional partonic channels (gq, ...) contribute 5%
- increase by only 8% relative to $pp \to t\bar{t}b\bar{b} \to l^+\nu_l jjb\bar{b}b\bar{b}$
- $\mathcal{O}\left((\alpha_s^3\alpha)^2\right) < 2\%$

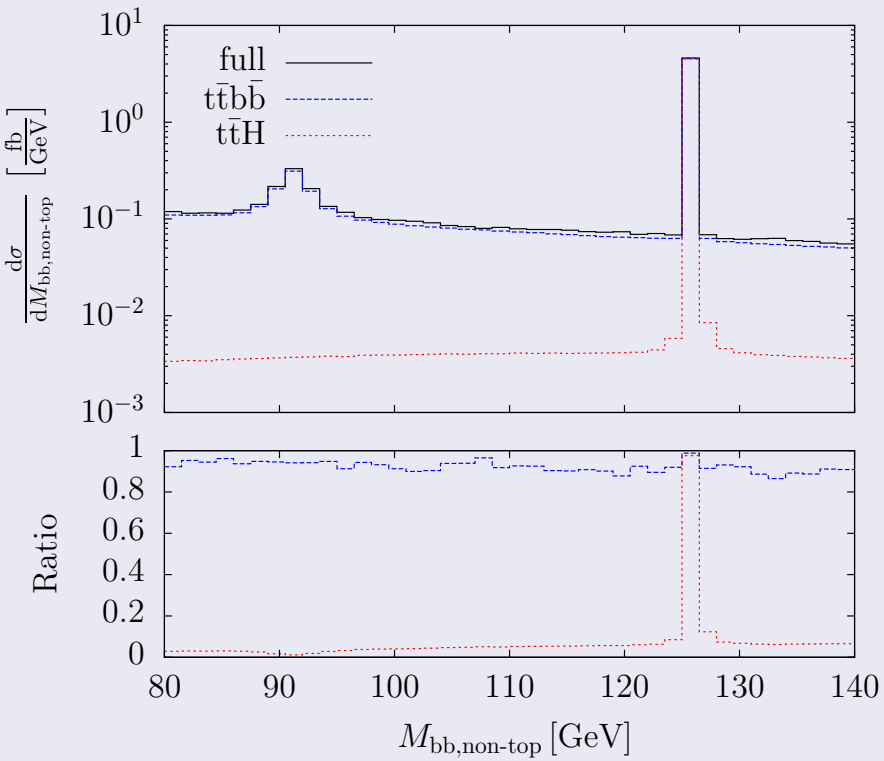
Irreducible background for distributions

Invariant mass of b-jet pair with smallest ΔR distance:



Higgs peak only weakly enhanced over combinatorial effect $t\bar{t}H/t\bar{t}b\bar{b} \sim 0.25$ (as for total cross section) outside resonances

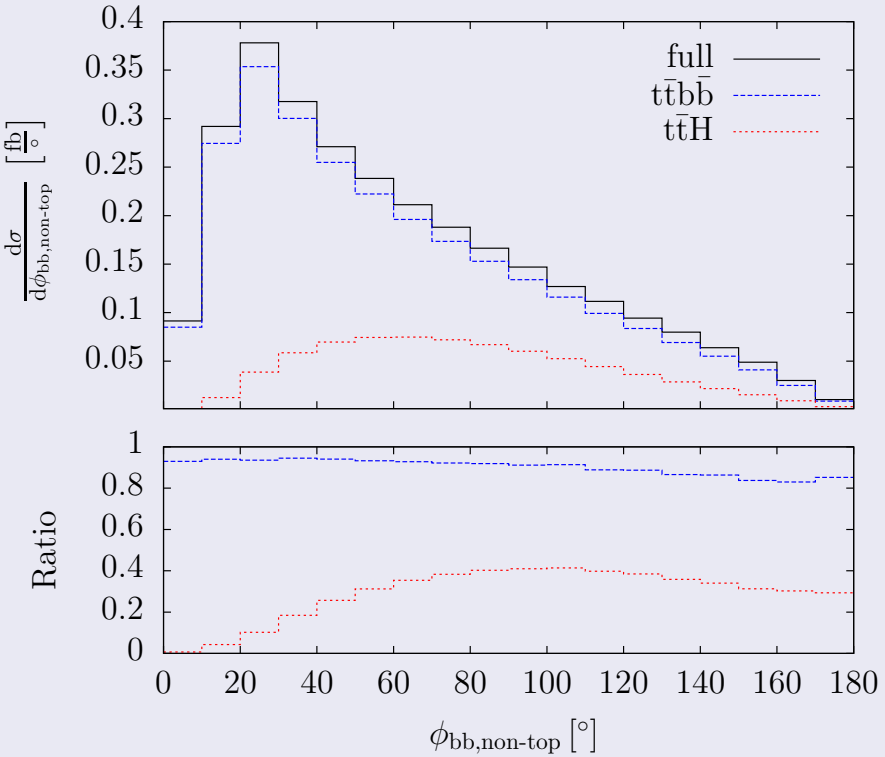
Invariant mass of b-jet pair not resulting from tops



- $t\bar{t}H/t\bar{t}b\bar{b}$ suppressed outside Higgs resonance
- Higgs and Z resonance well tagged

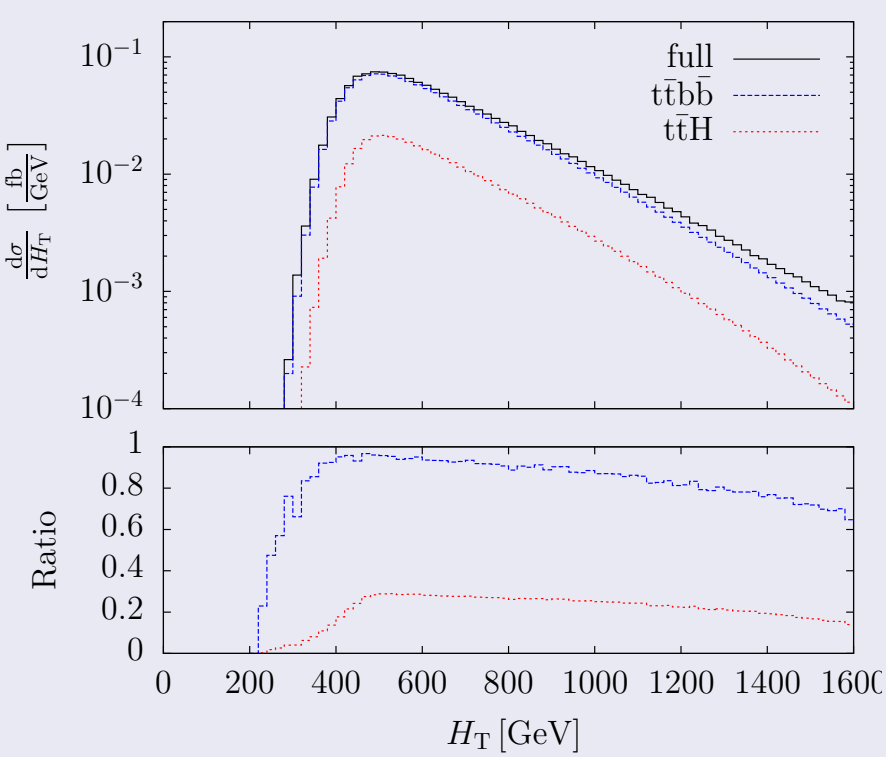
Irreducible background for distributions

Azimuth between non-top b-jet pair



- background peaked at small angles ($b\bar{b}$ pair dominantly from gluons)
- signal prefers larger angles (massive Higgs boson)

Sum of all transverse energies H_T

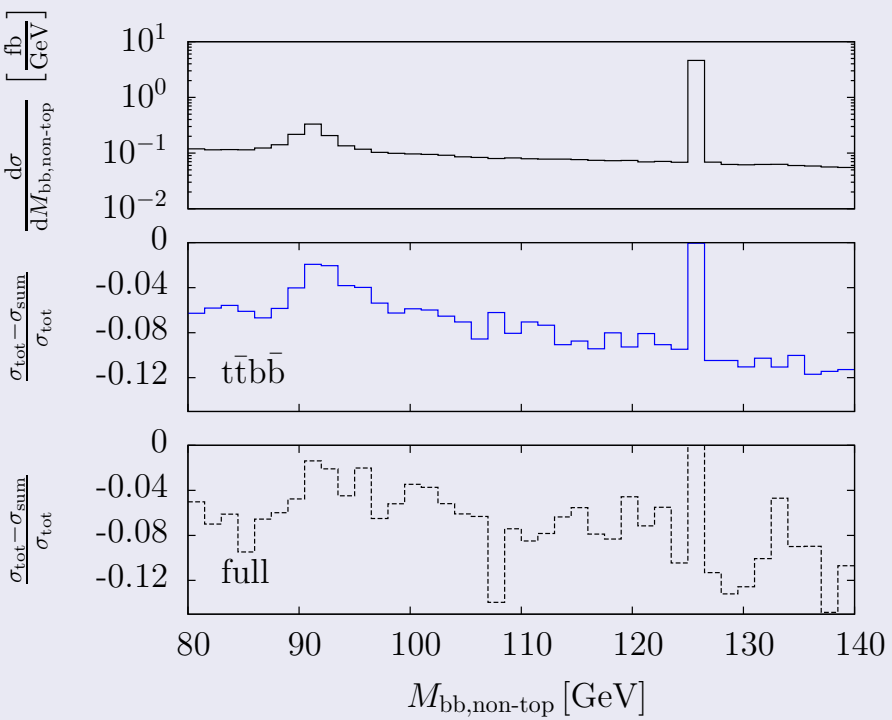


- signal suppressed for small H_T ($t\bar{t}H$ threshold)
- signal drops faster for large H_T (intermediate massive particles)

Interference effects on distributions

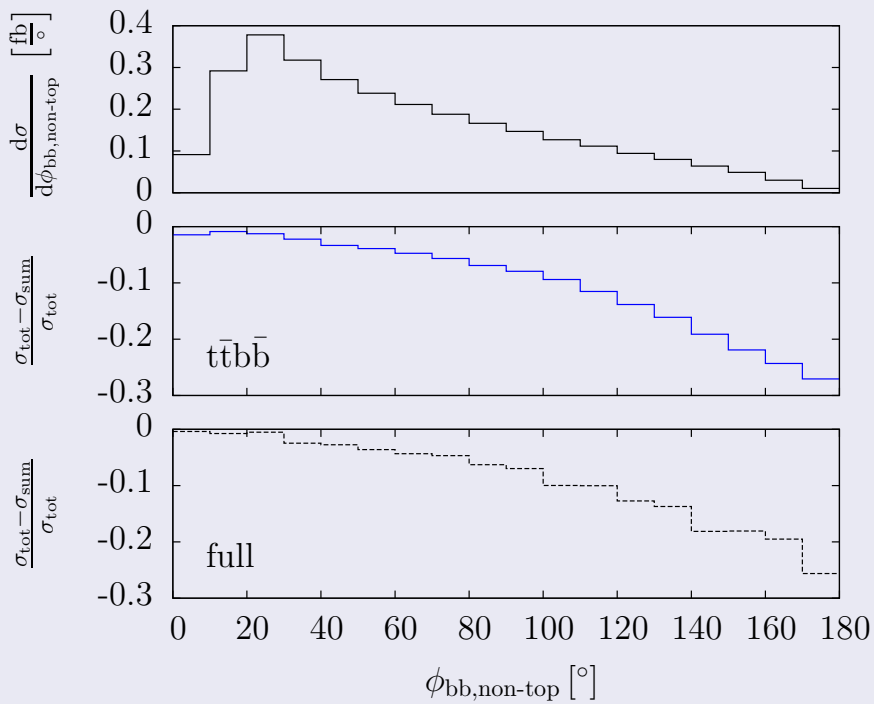
Constant shift of -5% for most contributions with some exceptions

Invariant mass of non-top $b\bar{b}$ pair



interference varies between 0 and -10%

Azimuth between non-top $b\bar{b}$ pair



large interference for large angles (suppressed cross section)

Conclusions and Outlook

Conclusions

- leading-order analysis of $pp \to l^+\nu_l jjb\bar{b}b\bar{b}$
- irreducible background $\sim 2.6 \times$ signal
- $pp \to t\bar{t}b\bar{b} \to l^+\nu_l jjb\bar{b}b\bar{b}$ describes full process within 10%
- sizeable interferences of -5% between QCD and EW diagrams
  flat for most but not all distributions

Outlook

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

- less subprocesses and integration channels contributing
- no jets and only two b-jets $\Rightarrow$ no combinatorial background
- no Higgs decay $\Rightarrow$ massless bottom quarks possible $\Rightarrow$ use of massless Catani–Seymour dipoles
- calculation follows in may respects $pp \to W^+W^-b\bar{b}$, e.g. same Catani–Seymour dipoles Denner, Dittmaier, Kallweit, Pozzorini '11, '12

Thank you for your attention!

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

Scale Choices

$$\mu_{\text{fix}} = \mu_R = \mu_F = \frac{1}{2}\left(2m_t + m_H\right) = 236\,\text{GeV} \tag{6}$$

$$\mu_{\text{dyn}} = \mu_R = \mu_F = \left(m_{T,t}\, m_{T,\bar{t}}\, m_{T,H}\right)^{\frac{1}{3}} \quad \text{with} \quad m_T = \sqrt{m^2 + p_T^2}, \tag{7}$$

Results

μ_0	ch.	σ_{LO} [fb]	σ_{NLO} [fb]	K
μ_{dyn}	gg	$1.6001(1)^{+33.8\%}_{-23.6\%}$	$2.017(4)^{-16.3\%}_{+1.0\%}$	1.260(2)
	$q\bar{q}$	$0.67786(5)^{+24.1\%}_{-18.1\%}$	$0.492(1)^{-39.6\%}_{+17.2\%}$	0.726(2)
	$g\overset{(-)}{q}$		$0.1341(4)^{+297\%}_{-152\%}$	
	pp	$2.2780(1)^{+30.9\%}_{-22.0\%}$	$2.643(4)^{-4.7\%}_{-3.7\%}$	1.160(2)
μ_{fix}	gg	$1.5776(1)^{+34.0\%}_{-23.7\%}$	$1.997(4)^{-16.5\%}_{+1.0\%}$	1.266(2)
	$q\bar{q}$	$0.67498(5)^{+24.3\%}_{-18.2\%}$	$0.494(1)^{-39.3\%}_{+17.0\%}$	0.732(2)
	$g\overset{(-)}{q}$		$0.1266(4)^{+310\%}_{-158\%}$	
	pp	$2.2526(1)^{+31.1\%}_{-22.1\%}$	$2.618(4)^{-5.0\%}_{-3.7\%}$	1.162(2)