NLO predictions on the ratio of $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ cross sections at the LHC

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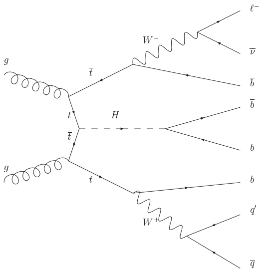
arXiv:1403.2046 [hep-ph]

Introduction and motivations

$t\bar{t}H(H \to b\bar{b})$: benchmark channel for studying Higgs boson properties

- gives direct access to the top-Higgs and bottom-Higgs Yukawa couplings
  $\to$ See L. Reina's talk
- benefits from new strategies to improve signal-to-background separation
  $\to$ See B. Mele's talk



Experimental signature (*e.g.* semi-leptonic ch.)

- One isolated lepton + missing E_T
- High jet multiplicity with multiple b-tags

Challenges

- Identification of b-jets (b-tagging)
- Reconstruction of top and H decays

Requires good control over dominant QCD backgrounds: $t\bar{t}b\bar{b}$, $t\bar{t}jj$

The cross section ratio

Idea

- Instead of extracting the cross section for $pp \to t\bar{t}b\bar{b}$, measure the $t\bar{t}b\bar{b}$ production rate normalized to the total $t\bar{t}jj$ sample:

$$R = \frac{\sigma(pp \to t\bar{t}b\bar{b})}{\sigma(pp \to t\bar{t}jj)}$$

Advantages

- More accurate measurement: common systematics are cancelled in the ratio (jet reconstruction efficiency, luminosity ...)
- More accurate prediction(?): theoretical uncertainties of dominant QCD backgrounds might be reduced in case of strong *correlations* between the two processes

How much correlated are the $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ backgrounds?

$t\bar{t}b\bar{b}$ / $t\bar{t}jj$ backgrounds: state of the art

NLO QCD

- $pp(p\bar{p}) \rightarrow t\bar{t}b\bar{b}$ — Bredenstein, Denner, Dittmaier and Pozzorini (2009, 2010)
  G.B, Czakon, Papadopoulos, Pittau, Worek (2009); Worek (2011)
- $pp(p\bar{p}) \rightarrow t\bar{t}jj$ — G.B, Czakon, Papadopoulos, Worek (2010, 2011)

NLO QCD + Parton Shower

- $pp \rightarrow t\bar{t}b\bar{b}$ — Kardos and Trocsanyi (2013)
  Cascioli, Maierhoefer, Moretti, Pozzorini and Siegert (2013)
- $pp \rightarrow t\bar{t}jj$ — Hoeche, Krauss, Maierhoefer, Pozzorini, Schonherr and Siegert (2014)

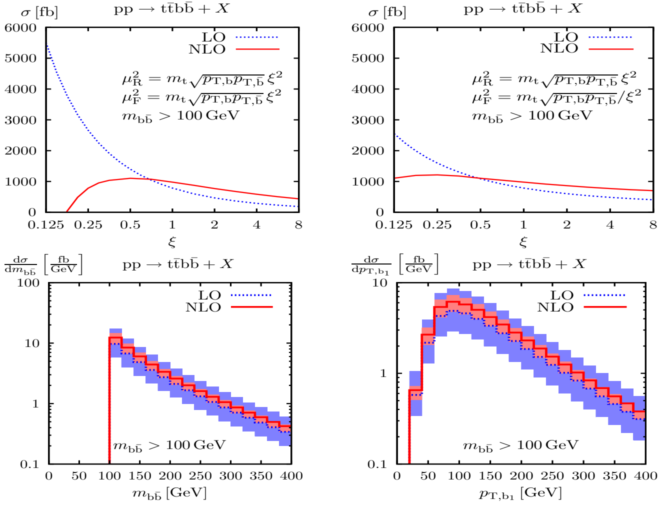
Accurate predictions on the ratio demand a systematic analysis of $t\bar{t}b\bar{b}$ and $t\bar{t}jj$

Lessons from the past...

(1) using $\mu^2 = m_t^2$, NLO QCD corrections to $pp \to t\bar{t}b\bar{b}$ are large ($\sim 77\%$)

Dynamical scale improves stability: $\mu^2 = m_t\sqrt{p_{T,b}\,p_{T,\bar{b}}}$

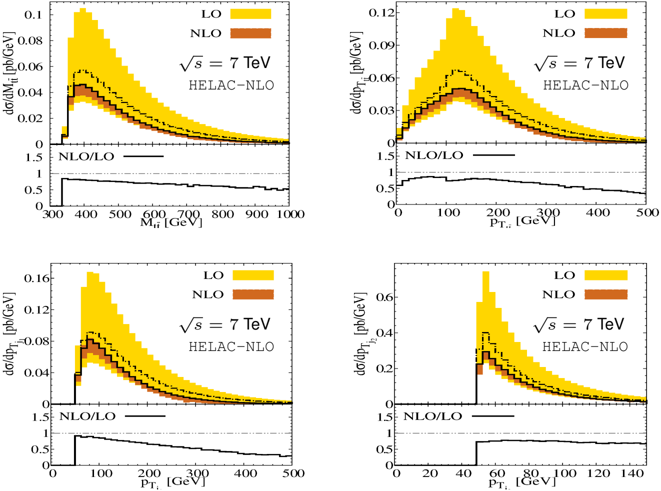
Bredenstein, Denner, Dittmaier and Pozzorini, 1001.4006 [hep-ph]



Lessons from the past...

(2) NLO QCD corrections to $pp \to t\bar{t}jj$ are fairly moderate using $\mu^2 = m_t^2$

G.B., Czakon, Papadopoulos and Worek, arXiv:1108.2851 [hep-ph]



Existing calculations are based on different setups, parameters, PDFs ...

This makes a determination of the cross section ratio possible only at the price of introducing undesired additional theoretical uncertainties

We want to perform a systematic analysis of $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ backgrounds and extract predictions for the cross section ratio accurate at the NLO$^{(*)}$

Our goals

- analyse (un)correlations between $t\bar{t}b\bar{b}$ and $t\bar{t}jj$
- assess realistic theoretical uncertainties
- assist LHC searches and compare with the available data (CMS)

(*) Top quark decays and Parton Shower effects have been not taken into account in this study. We will motivate why we expect them not to affect significantly our conclusions in the considered kinematical range

Outline of the analysis

- setup of the kinematical range
- analysis of the $t\bar{t}$ system and its jet activity in $t\bar{t}b\bar{b}$ and $t\bar{t}jj$
- extraction of the ratio and scale uncertainty estimates
- comparison with the available CMS data at $\sqrt{s} = 8$ TeV

I.
Setting up the range

As a preliminary step, we need to identify in which kinematical range our fixed-order predictions can be considered reliable

A comparison with results matched to Parton Shower helps us to estimate which phase space regions can be safely investigated within our analysis

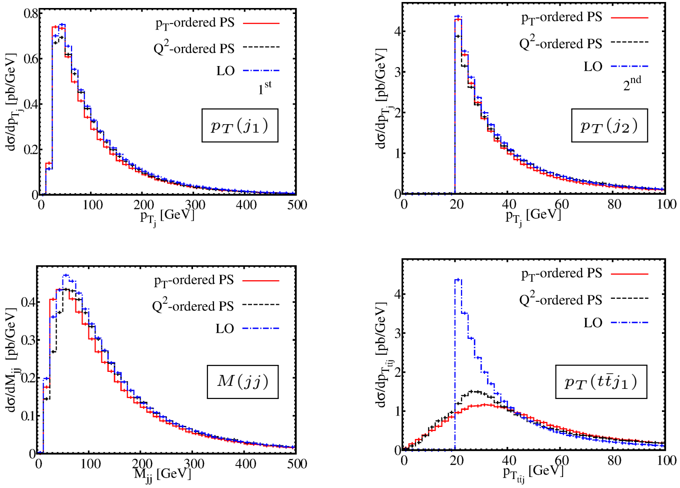
We focus on the benchmark process $pp \to t\bar{t}jj$ and compare genuine fixed order (LO) predictions with results matched to PYTHIA 6.4 shower (LO+PS)

Basic setup:

$\sqrt{s} = 8$TeV	$p_T(j) > 20$ GeV	$\lvert y(j)\rvert < 2.5$	$\Delta R(jj) > 0.5$
CT09MC1 PDF	anti-k_T algorithm	$\mu_R = \mu_F = m_t = 173.5$ GeV	

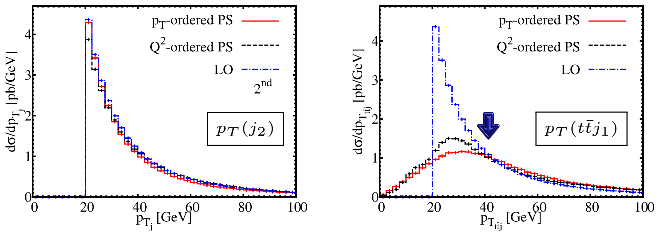
$pp \to t\bar{t}jj$: LO vs LO+PS results

G.B and M.Worek, arXiv:1403.2046 [hep-ph]



j_1 $(j_2) = 1^{st}(2^{nd})$ hardest jet

Interpretation:



- LO: kinematics sets $p_T(t\bar{t}j_1) = p_T(j_2)$ $\Rightarrow$ the two distributions coincide
- LO+PS: correlation between the two observables is lost due to extra jet activity. Sudakov suppression starts below $p_T(t\bar{t}j) \simeq 40$ GeV
- Dominant higher-order effects are likely to endanger perturbative stability at low p_T's. Resummation of higher orders is needed

Special restrictions on jet p_T are required for a safe fixed-order analysis

Final setup

Phase space cuts

- $p_T(j) > 40$ GeV , $|y(j)| < 2.5$, $\Delta R(jj) > 0.5$, anti-k_T jet algorithm

Scale choice

- $t\bar{t}b\bar{b}$: $\mu_R^2 = \mu_F^2 \equiv m_t \sqrt{p_{T_b}\, p_{T_{\bar{b}}}}$ arXiv:1001.4006 [hep-ph]
- $t\bar{t}jj$: $\mu_R^2 = \mu_F^2 \equiv m_t^2$ arXiv:1002.4009 [hep-ph]
- scale uncertainty estimated by varying scales up and down by a factor 2

PDF set

- CT09MC1 (LO), CT10 (NLO)

Collider energies

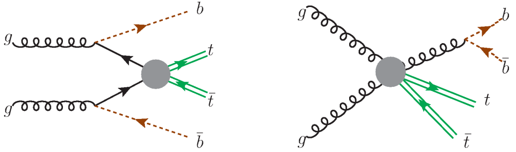
- $\sqrt{s} = 7, 8, 13$ TeV

NLO results obtained with the help of the package `HELAC-NLO`

HELAC-NLO Collab., Comput.Phys.Commun. 184 (2013) 986-997, arXiv:1110.1499 [hep-ph]

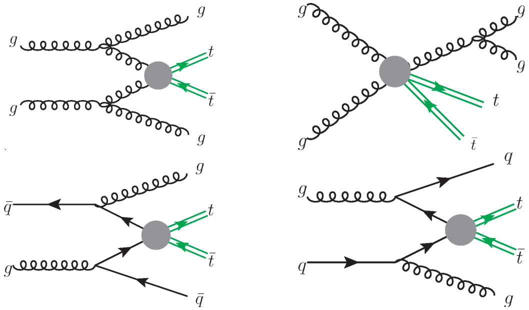
II.
Looking for correlations

Dominant production channels



$pp \rightarrow t\bar{t}b\bar{b}$

gg
channel



$pp \rightarrow t\bar{t}jj$

gg
channel

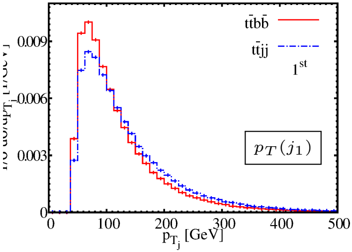
qg
channel

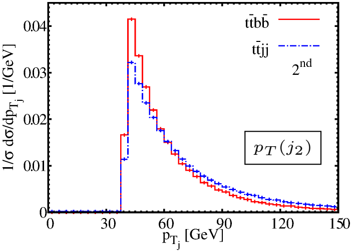
Interplay of different mechanisms: what's the impact on correlations?

Differential cross sections

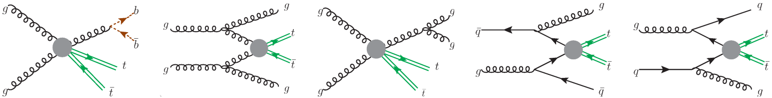
Comparing shapes at NLO: distributions normalized to unit

1. Transverse momentum of jets





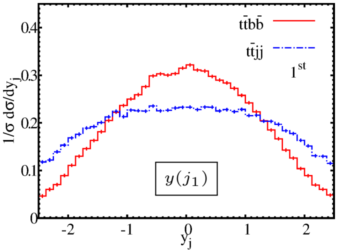
$t\bar{t}jj$ has (slightly) harder p_T spectrum than $t\bar{t}b\bar{b}$

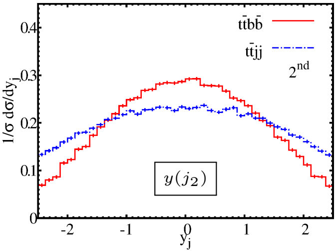


Differential cross sections

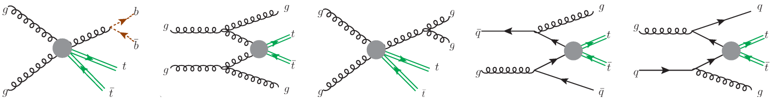
Comparing shapes at NLO: distributions normalized to unit

2. Rapidity of jets





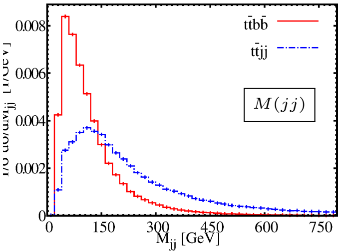
b-jets from $t\bar{t}b\bar{b}$ prefer central regions of the detector

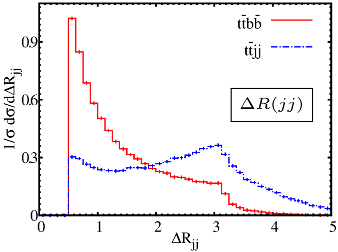


Differential cross sections

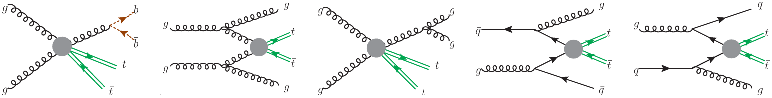
Comparing shapes at NLO: distributions normalized to unit

3. Invariant mass and ΔR of two hardest jets





Jet pairs from $t\bar{t}b\bar{b}$ prefer small-angle emission



In summary

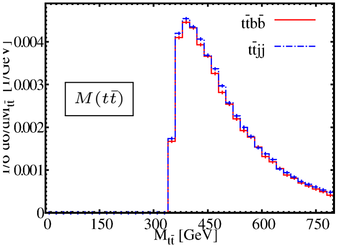
- different production mechanisms dominate the two background processes
- $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ show different properties in the jet activity, mainly in angular and invariant mass distributions

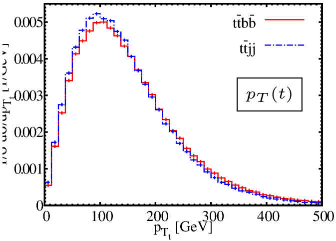
What can be said about the underlying (common) $t\bar{t}$ production?

Differential cross sections

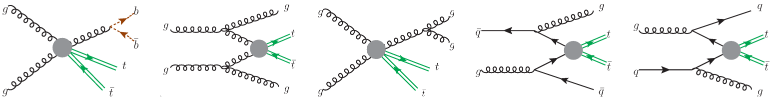
Comparing shapes at NLO: distributions normalized to unit

4. Invariant mass and p_T of the $t\bar{t}$ system





The underlying $t\bar{t}$ production shows some correlation



III. NLO predictions for the ratio $t\bar{t}b\bar{b}$ / $t\bar{t}jj$

Does the ratio show improved predictive power w.r.t absolute cross sections?

G.B and Worek, arXiv:1403.2046 [hep-ph]

CM energy	$\sigma^{\rm NLO}_{pp\to t\bar{t}b\bar{b}}$ [fb]	$\sigma^{\rm NLO}_{pp\to t\bar{t}jj}$ [pb]
$\sqrt{s} = 7$ TeV	$142.2^{+24.1(\mathbf{17}\%)}_{-34.6(\mathbf{24}\%)}$	$13.55^{-1.66(\mathbf{14}\%)}_{-1.92(\mathbf{14}\%)}$
$\sqrt{s} = 8$ TeV	$229.3^{+40.7(\mathbf{18}\%)}_{-55.7(\mathbf{24}\%)}$	$20.97^{-3.25(\mathbf{15}\%)}_{-2.79(\mathbf{13}\%)}$
$\sqrt{s} = 13$ TeV	$1078.3^{+222.1(\mathbf{20}\%)}_{-249.7(\mathbf{23}\%)}$	$85.5^{-18.3(\mathbf{21}\%)}_{-8.4(\mathbf{10}\%)}$

If processes are indeed correlated, the answer is yes. Ratios of cross sections for a single process at different CM energies provide interesting examples

Mangano and Rojo, JHEP 1208, 010 (2012) [arXiv:1206.3557 [hep-ph]]

Just one example, assuming correlation:

$$R^{t\bar{t}b\bar{b}}_{8,7} \equiv \sigma_{t\bar{t}b\bar{b}}(8\text{ TeV}) \,/\, \sigma_{t\bar{t}b\bar{b}}(7\text{ TeV}) = 1.6125^{+0.0111(\mathbf{0.7}\%)}_{+0.0009(\mathbf{0.06}\%)}$$

What about $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$?

We estimate the scale uncertainty of the ratio exploring different approaches

$$R^{NLO} \equiv \frac{\sigma^{NLO}_{t\bar{t}b\bar{b}}(\xi_1\,\mu_0)}{\sigma^{NLO}_{t\bar{t}jj}(\xi_2\,\mu_0')} \qquad \xi_1, \xi_2 \in \{\,0.5\,,\,1\,,2\,\}$$

”Uncorrelated”

- error band is the envelope of all possible combinations of (ξ_1, ξ_2)

”Correlated”

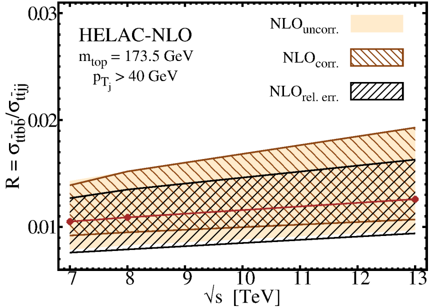
- only combinations $(\xi_1, \xi_2) \in \{(0.5, 0.5), (1, 1), (2, 2)\}$ are considered

”Relative-error”

- relative errors of the absolute cross sections are added in quadrature

NLO predictions on the ratio

CM energy	*uncorrelated*	*correlated*	*relative-error*
$\sqrt{s} = 7$ TeV	$0.0105^{+0.0038(\mathbf{36}\%)}_{-0.0026(\mathbf{25}\%)}$	$0.0105^{+0.0034(\mathbf{32}\%)}_{-0.0013(\mathbf{12}\%)}$	$0.0105^{+0.0022(\mathbf{21}\%)}_{-0.0029(\mathbf{28}\%)}$
$\sqrt{s} = 8$ TeV	$0.0109^{+0.0043(\mathbf{39}\%)}_{-0.0026(\mathbf{24}\%)}$	$0.0109^{+0.0043(\mathbf{39}\%)}_{-0.0014(\mathbf{13}\%)}$	$0.0109^{+0.0026(\mathbf{24}\%)}_{-0.0030(\mathbf{27}\%)}$
$\sqrt{s} = 13$ TeV	$0.0126^{+0.0067(\mathbf{53}\%)}_{-0.0029(\mathbf{23}\%)}$	$0.0126^{+0.0067(\mathbf{53}\%)}_{-0.0019(\mathbf{15}\%)}$	$0.0126^{+0.0037(\mathbf{29}\%)}_{-0.0032(\mathbf{25}\%)}$



G.B and Worek, arXiv:1403.2046 [hep-ph]

Different approaches give comparable error estimates

The *uncorrelated* approach is the most conservative one

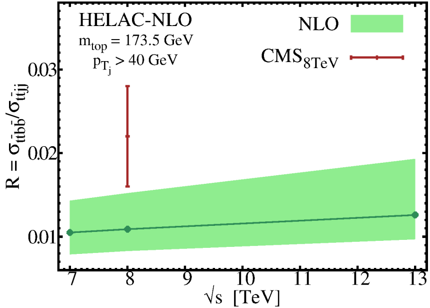
Comparison with LHC data

Current CMS result for $\sqrt{s} = 8$ TeV – 19.6 fb^{-1} – dilepton decay mode:

$p_{T_j} > 20$ GeV : $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj} = 0.023 \pm 0.003$ (stat.) $\pm\, 0.005$ (syst.)

$p_{T_j} > 40$ GeV : $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj} = 0.022 \pm 0.004$ (stat.) $\pm\, 0.005$ (syst.)

CMS PAS TOP-13-010



G.B and Worek, arXiv:1403.2046 [hep-ph]

Direct comparison is possible for $p_{T_j} > 40$ GeV

Theoretical error band based on the *uncorrelated* hypothesis

Summary and conclusions

- We have presented the first consistent NLO predictions for the cross section ratio $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$ together with an estimate of its scale uncertainty
- Different jet activity in $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ has negative impact on correlations (but the $t\bar{t}$ system shows similarities)
- With a scale uncertainty of $20\% - 30\%$, the ratio shows the same theoretical accuracy than the individual cross sections
- Top quark decays and parton shower not included in the analysis. Minimal impact expected in the considered kinematical range ($p_{T_j} > 40$ GeV). Parton Shower might play an important role for looser p_{T_j} cuts
- Comparison with CMS data at 8 TeV shows agreement within 1.5σ. A new measurement based on complete data sample is underway