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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HP2: High Precision for Hard Processes

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In collaboration with M. Worek (RWTH Aachen)

Based on **JHEP 1407 (2014) 135**, arXiv:1403.2046 [hep-ph]

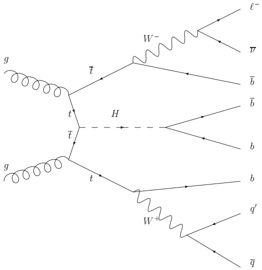
Introduction and motivations

After the discovery of a Higgs boson, the focus is now on the precision measurement of its couplings

$pp \to t\bar{t}H(H \to b\bar{b})$ is a benchmark channel:

- gives direct access to the top-Higgs and bottom-Higgs Yukawa couplings
- benefits from new strategies to improve signal-to-background separation

Biswah, Frederix, Gabrielli and Mele, arXiv:1403.1790 [hep-ph]



Experimental signature (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
- Large QCD backgrounds: $t\bar{t}b\bar{b}$, $t\bar{t}jj$

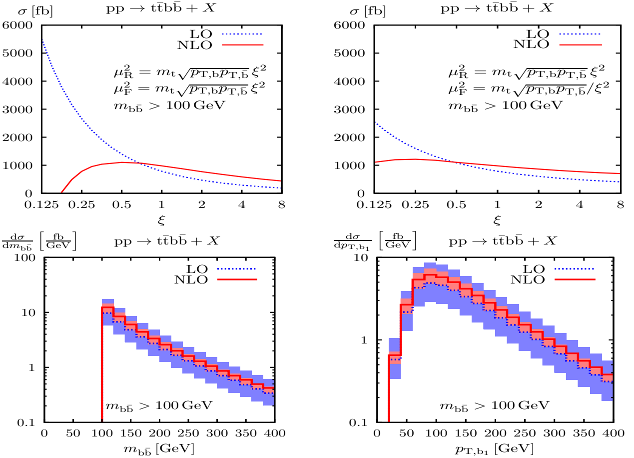
Accurate knowledge of dominant QCD backgrounds is fundamental

$t\bar{t}b\bar{b}$ / $t\bar{t}jj$ backgrounds: what we learned

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

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

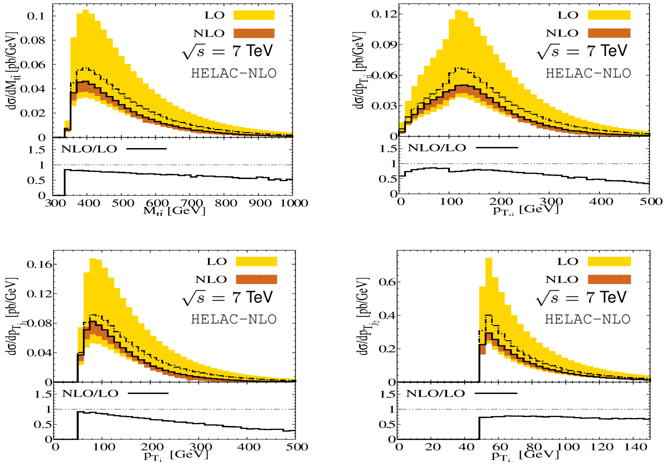
Bredenstein, Denner, Dittmaier and Pozzorini, 1001.4006 [hep-ph]



$t\bar{t}b\bar{b}$ / $t\bar{t}jj$ backgrounds: what we learned

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

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



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

Fixed order @ NLO

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

PS matching @ NLO

- $pp \to t\bar{t}b\bar{b}$ Kardos and Trocsanyi (2013), Garzelli, Kardos and Trocsanyi (2014)
  Cascioli, Maierhoefer, Moretti, Pozzorini and Siegert (2013)

PS + full jet merging @ NLO

- $pp \to t\bar{t} + 0, 1, 2$ jets Hoeche, Krauss, Maierhoefer, Pozzorini, Schonherr and Siegert (2014)

Residual scale uncertainties at the level of 20%

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:

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

See studies in: CMS PAS TOP-12-024 and CMS PAS TOP-13-010

Advantages

- More accurate measurement: common systematics are cancelled in the ratio (jet reconstruction efficiency, luminosity ...)
- More accurate prediction[?]: theoretical uncertainties might be reduced in case the two processes are correlated

How strong are correlations between $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ backgrounds?

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 NLO analysis of $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ backgrounds and extract predictions for the cross section ratio

Our goals

- analyse possible 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)

Caveat

- assuming *stable* top quarks (∗)
- this is a *fixed-order* analysis

(∗) At LO, the impact of top quark decays on the ratio is less than 5%

Outline of the analysis

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

I.
Setting up the range

As a preliminary step, we need to identify the kinematical region where 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

Let's 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)

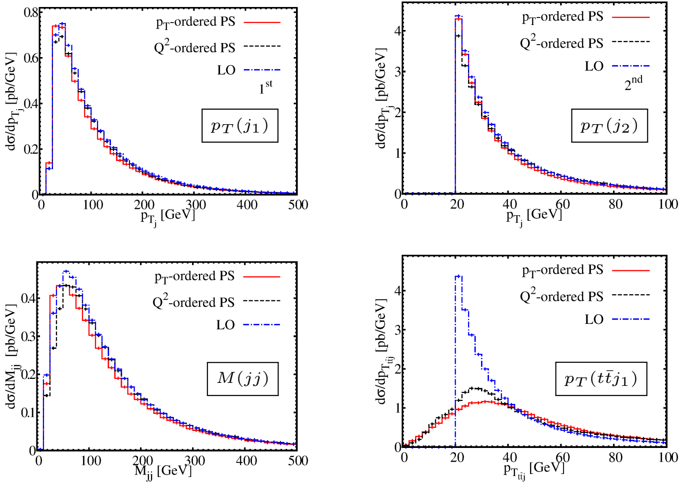
Basic setup:

$\sqrt{s} = 8$TeV $p_T(j) > 20$ GeV $|y(j)| < 2.5$ $\Delta R(jj) > 0.5$

CT09MC1 PDF   anti-k_T algorithm $\mu_R = \mu_F = m_t = 173.5$ GeV

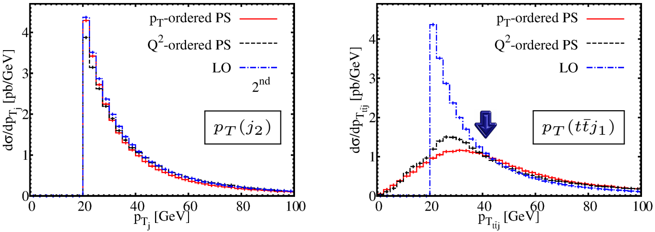
$pp \to t\bar{t}jj$: LO vs LO+PS results

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

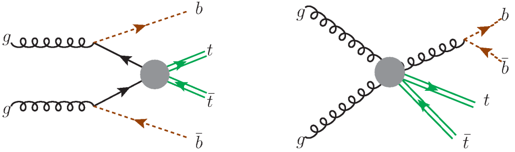
- $\sqrt{s} = 7, 8, 13$ TeV

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]

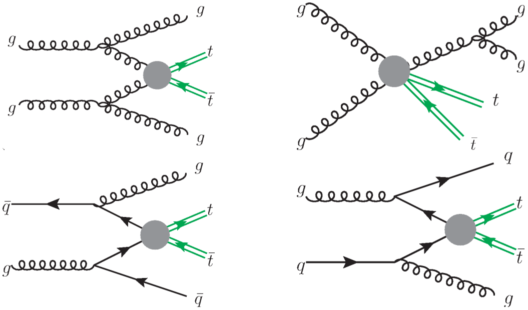
II.
Looking for correlations

Dominant production channels



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

gg
channel



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

gg
channel

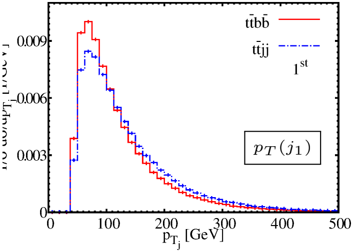
qg
channel

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

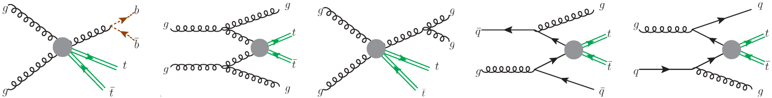
Differential cross sections

Comparing NLO shapes: distributions normalized to unit

1. Transverse momentum of jets



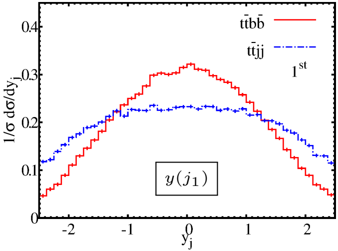
$t\bar{t}jj$ has (slightly) harder p_T spectrum than $t\bar{t}b\bar{b}$

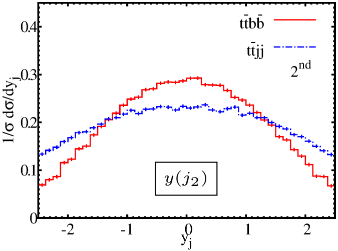


Differential cross sections

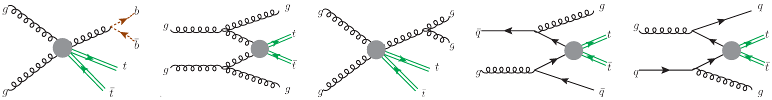
Comparing NLO shapes: distributions normalized to unit

2. Rapidity of jets





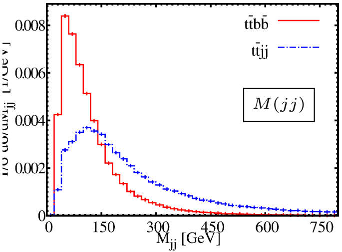
b-jets from $t\bar{t}b\bar{b}$ prefer central regions of the detector

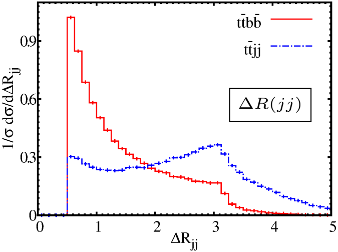


Differential cross sections

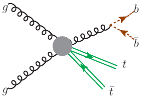
Comparing NLO shapes: distributions normalized to unit

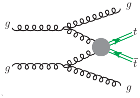
3. Invariant mass and ΔR of two hardest jets

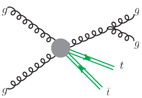


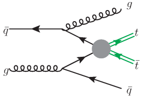


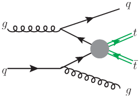
Jet pairs from $t\bar{t}b\bar{b}$ prefer small-angle emission











In summary

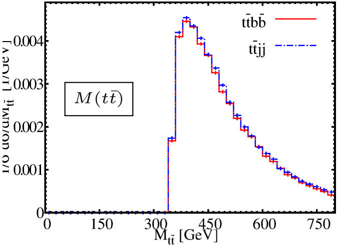
- different production mechanisms dominate the two background processes
- $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ show different properties in the jet activity, mainly in angular and invariant mass distributions

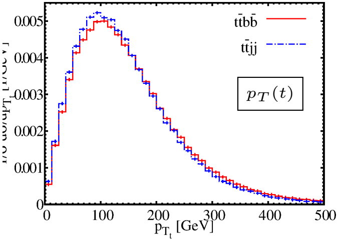
What can be said about the underlying $t\bar{t}$ production?

Differential cross sections

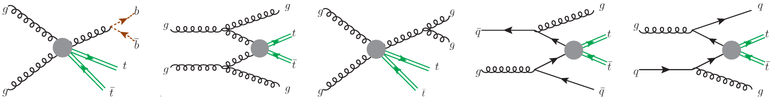
Comparing shapes at NLO: distributions normalized to unit

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





The underlying $t\bar{t}$ production shows a stronger 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"

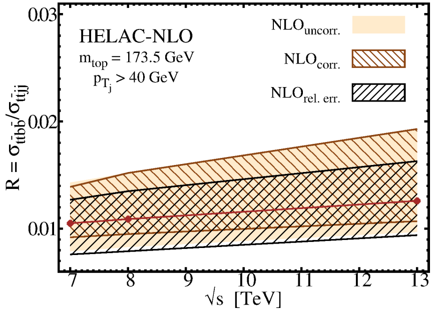
- only combinations $(\xi_1, \xi_2) \in \{(0.5, 0.5), (1, 1), (2, 2)\}$ are considered

"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

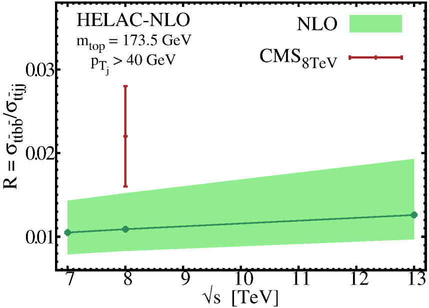
Comparison with LHC data

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 scale uncertainties
- 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. Shower effects play an important role at low jet p_T's ($p_{T_j} < 40$ GeV)
- Comparison with CMS data at 8 TeV shows agreement within $1.5\,\sigma$. New measurement based on complete data sample is underway