Precise predictions for $t\bar{t} + E_T^{miss}$ at the LHC

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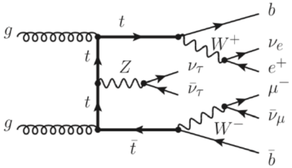
with H. B. Hartanto, M. Kraus, T. Weber and M. Worek

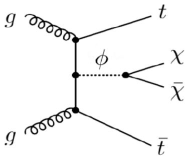
arXiv:1907.09359 [hep-ph]

Introduction

This talk will focus on recent progress in the theoretical understanding of the SM process $pp \to t\bar{t}Z(Z \to \nu\bar{\nu})$ ...



... having in mind a wider perspective: DM searches in $t\bar{t} + E_T^{miss}$ at colliders



Motivation

Dark Matter studies lie at the interface of astrophysics, cosmology and collider physics

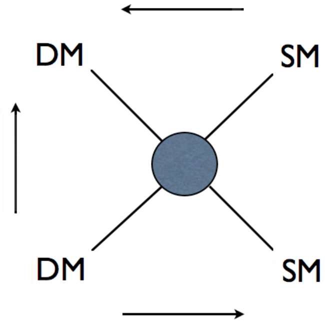
Collider searches

[processes with large $\not{E}_T$] $\longrightarrow$ Tevatron, LHC ...

Direct detection

[underground nuclear recoil experiments]

$\hookrightarrow$ XENON, LUX, CDMS, DAMA ...



Indirect detection

[DM annihilation in the galaxy] $\longrightarrow$ Planck, FermiLAT ...

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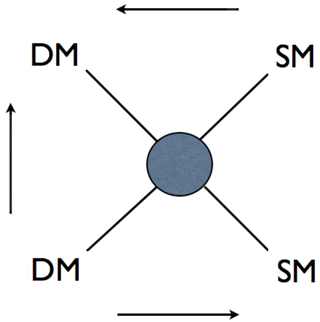


Our focus is on DM searches at **LHC**

Indirect detection

[DM annihilation in the galaxy]

$\longrightarrow$ Planck, FermiLAT ...

Motivation

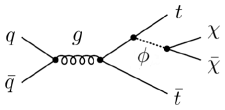
It is useful to study DM using *simplified models*

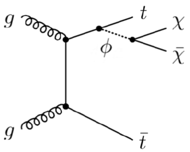
- assume *mediator* (ϕ) which couples to both SM and DM particles
  $\hookrightarrow$ CP nature of mediator is unknown: scalar, pseudo-scalar, ...?

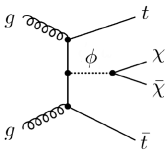
- couplings of ϕ to SM particles constrained by precision measurements
  $\hookrightarrow$ *Minimal Flavor Violation* (MFV) hypothesis is often quoted: couplings of ϕ to the visible sector (SM) proportional to fermion masses

D'ambrosio, Giudice, Isidori and Strumia, hep-ph/0207036

$\hookrightarrow$ in models with MFV, DM couples preferentially to top quarks



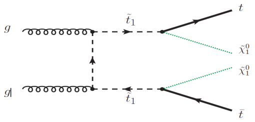


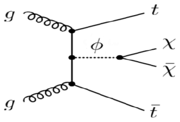


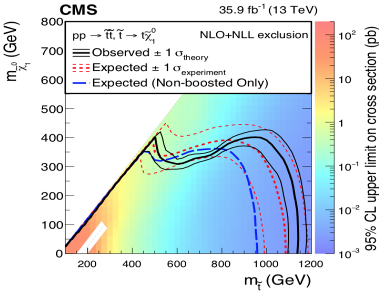
Arina *et al.*, arXiv:1605.09242 [hep-ph]
Haisch, Pani and Polesello, arXiv:1611.09841 [hep-ph]

Motivation

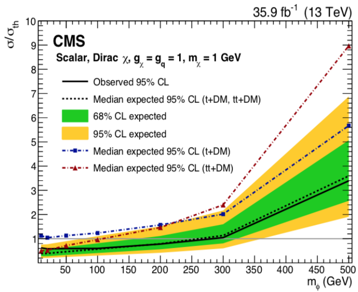
Recent examples of exclusion limits for SUSY or DM involving $t\bar{t} + E_T^{miss}$ interpreted in the context of simplified models







arXiv:1812.06302 [hep-ex]

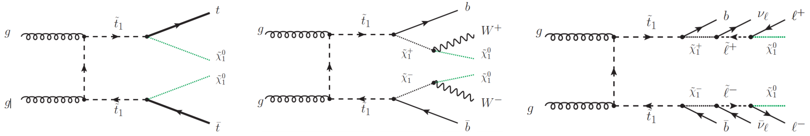


arXiv:1901.01553v2 [hep-ex]

Motivation

Also, various theoretical models predict viable DM candidates (WIMP's)

e.g. SUSY:



All these BSM processes have the typical signature of recoiling visible final states against large missing transverse energy (E_T^{miss})

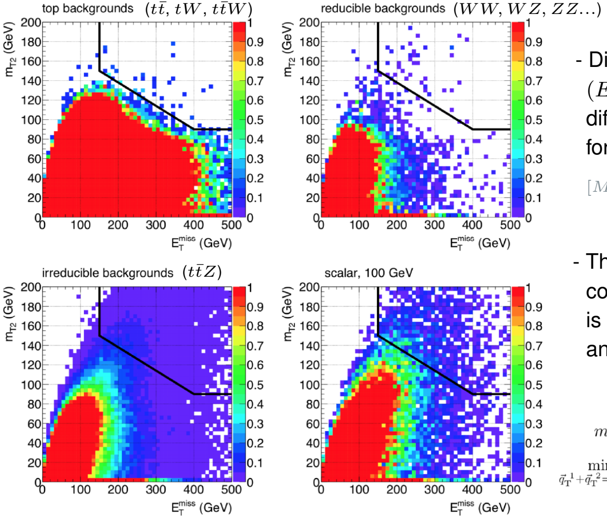
Various **SM backgrounds** can also resemble this signature:

- top backgrounds: $t\bar{t}$, $t\bar{t}W$, tW
- reducible backgrounds: WW, WZ, ZZ, $Z+$jets
- irreducible background: $t\bar{t}Z(Z \rightarrow \nu\bar{\nu})$

Motivation

Determining the CP nature of spin-0 mediators in $t\bar{t}$ + DM production

Haisch, Pani and Polesello, arXiv:1611.09841 [hep-ph]



- Distribution of events in the (E_T^{miss}, m_{T2}) plane for the different backgrounds and for one example of signal

  $[M_\phi = 100$ GeV , $M_\chi = 1$ GeV]

- The area in the upper right corner above the black line is the region selected in the analysis

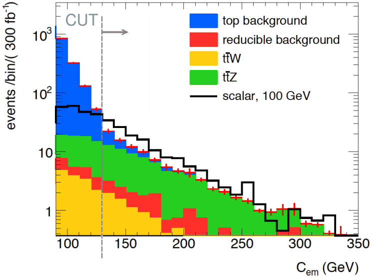
$$m^2_{\mathrm{T2}}(\vec{p}_{\mathrm{T}}^{\,\ell_i}, \vec{p}_{\mathrm{T}}^{\,\ell_j}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}) \equiv \min_{\vec{q}_{\mathrm{T}}^{\,1}+\vec{q}_{\mathrm{T}}^{\,2}=\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \left\{ \max\left[m^2_{\mathrm{T}}(\vec{p}_{\mathrm{T}}^{\,\ell_i}, \vec{q}_{\mathrm{T}}^{\,1}), m^2_{\mathrm{T}}(\vec{p}_{\mathrm{T}}^{\,\ell_j}, \vec{q}_{\mathrm{T}}^{\,2}) \right] \right\}$$

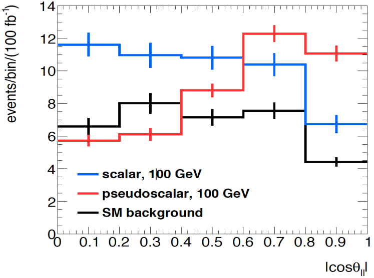
Motivation

To further reduce the top background, the following observable is considered:

$$C_{em} = m_{T2} + 0.2 \cdot \left(200 \text{ GeV} - E_T^{miss}\right)$$

Haisch, Pani and Polesello, arXiv:1611.09841 [hep-ph]





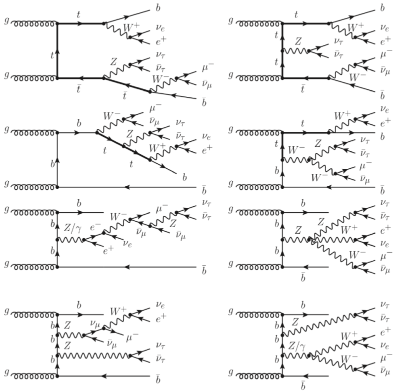
- With 300 fb^{-1}, assuming 20% systematics for SM backgrounds, it should be possible to resolve between the two CP hypotheses up to $M_\phi \approx 200$ GeV

- Discovery reach depends on syst. uncertainty of SM backgrounds, dominated by $t\bar{t}Z$

$\hookrightarrow$ a good understanding of $t\bar{t}Z$ is key to a possible discovery of DM in $t\bar{t} + E_T^{miss}$

SM $t\bar{t}Z$: state of the art

- NLO QCD $\rightarrow$ stable tops
  Lazopoulos *et al.*, '08
- NLO QCD $\rightarrow$ NWA with NLO decays
  Röntsch and Schulze '14
- NLOPS QCD
  Kardos, Garzelli and Trocsanyi '12
- NLOPS EW+QCD
  Frixione *et al.* '15
- NLO + NNLL
  Kulesza *et al.* '18 ; Broggio *et al.* '17,'19
- NLO QCD $\rightarrow$ off-shell, dilepton
  G.B., Hartanto, Kraus, Weber and Worek '19

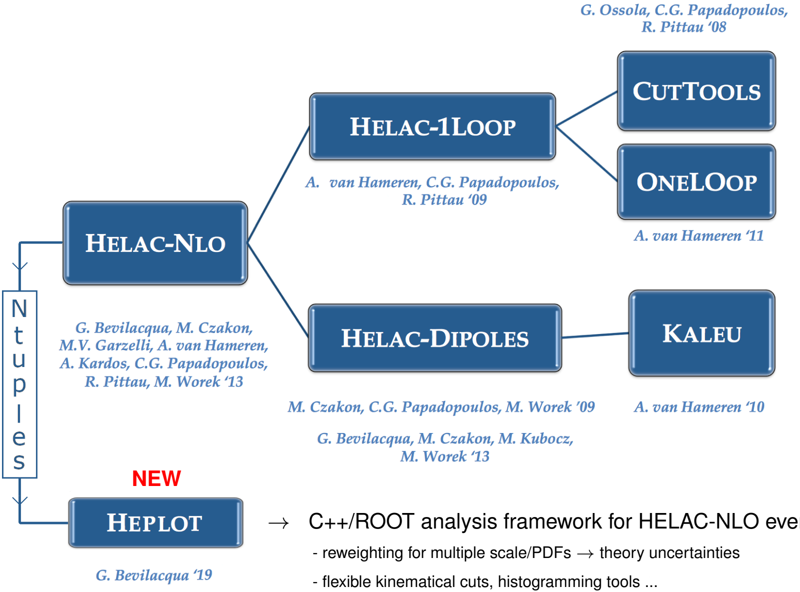


- In 1611.09841, $t\bar{t}Z$ events are generated with **Madgraph5_aMC@NLO** at LO and normalized with the NLO cross section ($\rightarrow$ *on-shell* top decays)

- Shape information is crucial to improve the reach for $t\bar{t} + E_T^{miss}$ searches

$\hookrightarrow$ we have performed a complete *off-shell* NLO calculation with **HELAC−NLO**

The HELAC-NLO framework



$\rightarrow$ C++/ROOT analysis framework for HELAC-NLO events

- reweighting for multiple scale/PDFs $\rightarrow$ theory uncertainties
- flexible kinematical cuts, histogramming tools ...

Setup and scales

- Dilepton channel: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\nu_\tau\bar{\nu}_\tau + X$ @ 13 TeV

- Cuts:

$p_{T,b} > 40$ GeV	$\lvert y_b \rvert < 2.5$	$\Delta R_{b\bar{b}} > 0.4$	$p_T^{miss} > 50$ GeV
$p_{T,\ell} > 30$ GeV	$\lvert y_\ell \rvert < 2.5$	$\Delta R_{\ell\ell} > 0.4$	$\Delta R_{\ell b} > 0.4$

- Scales:

$\mu_0 = m_t + \frac{m_Z}{2}$
$\mu_0 = \frac{H_T}{3}$
$\mu_0 = \frac{E_T}{3} = \frac{1}{3}\left(m_{T,t} + m_{T,\bar{t}} + p_{T,Z}\right)$
$\mu_0 = \frac{E'_T}{3} = \frac{1}{3}\left(m_{T,t} + m_{T,\bar{t}} + m_{T,Z}\right)$
$\mu_0 = \frac{E''_T}{3} = \frac{1}{3}\left(m_{T,t} + m_{T,\bar{t}}\right)$

$\rightarrow$ **Fixed** and **dynamical** scales, either "resonant aware" (E_T, E'_T, E''_T) or "blind" (H_T)

$$H_T = p_{T,e^+} + p_{T,\mu^-} + p_T^{miss} + p_{T,b_1} + p_{T,b_2}$$

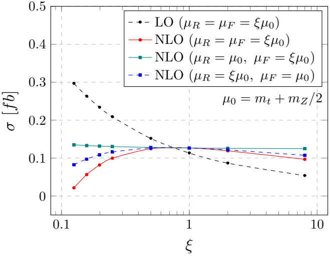
$$m_{T,i} = \sqrt{p_{T,i}^2 + m_i^2}$$

Total cross sections

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\nu_\tau\bar{\nu}_\tau$ – NLO cross section for various scale and PDF choices

G.B, Hartanto, Kraus, Weber and Worek, arXiv:1907.09359 [hep-ph]

$\sigma^{\rm NLO}$ [fb]	CT14	MMHT2014	NNPDF3.0	δ_{PDF}
$\mu_0 = \mathbf{m_t + m_Z/2}$	$0.1266^{+1,1\%}_{-5.9\%}$	$0.1275^{+1.1\%}_{-5.9\%}$	$0.1309^{+1.1\%}_{-6.0\%}$	3.4%
$\mu_0 = \mathbf{H_T/3}$	$0.1270^{+0.7\%}_{-6.8\%}$	$0.1278^{+0.7\%}_{-7.0\%}$	$0.1312^{+0.7\%}_{-6.9\%}$	3.3%
$\mu_0 = \mathbf{E_T/3}$	$0.1272^{+1.6\%}_{-6.8\%}$	$0.1279^{+1.6\%}_{-6.8\%}$	$0.1313^{+1.6\%}_{-6.9\%}$	3.2%
$\mu_0 = \mathbf{E'_T/3}$	$0.1268^{+1.5\%}_{-6.4\%}$	$0.1280^{+1.5\%}_{-6.4\%}$	$0.1315^{+1.5\%}_{-6.5\%}$	3.7%
$\mu_0 = \mathbf{E''_T/3}$	$0.1286^{+1.0\%}_{-4.7\%}$	$0.1295^{+1.0\%}_{-4.7\%}$	$0.1330^{+1.0\%}_{-4.8\%}$	3.4%



- Complete cross section for dilepton channel (e/μ) can be realized by multiplying results by 12:

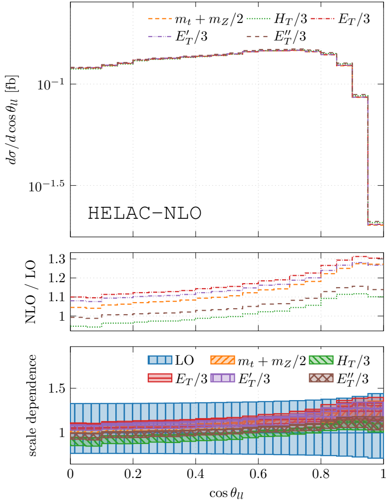
  $\sigma_{NLO}(t\bar{t}Z,$ dilept.$) \sim 1.5$ fb

- Scale uncertainties $\sim \mathcal{O}(5-7\%)$

- PDF uncertainties $\sim \mathcal{O}(3\%)$

Differential cross sections

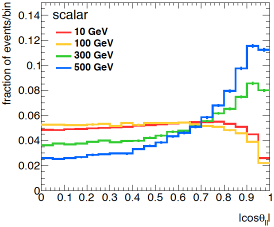
G.B, Hartanto, Kraus, Weber and Worek, arXiv:1907.09359 [hep-ph]



$$\cos\theta_{ll} = \tanh(\Delta y_{ll}/2)$$

- Sensitive to the nature of DM mediator

Haisch *et al.* '16

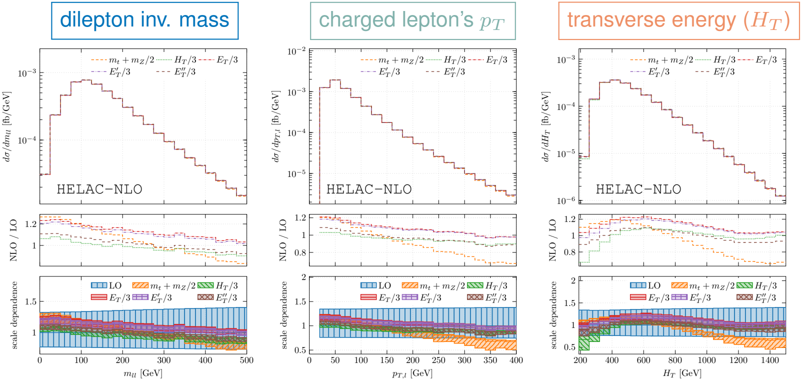


- Differential K-factors far from constant!
  - $\mu = m_t + m_Z/2$: $+4\% \leftrightarrow 27\%$
  - $\mu = H_T/3$: $-5\% \leftrightarrow 10\%$
  - $\mu = E''_T/3$: $-1\% \leftrightarrow 14\%$

Differential cross sections

Let's also check some *dimensionful* observable...

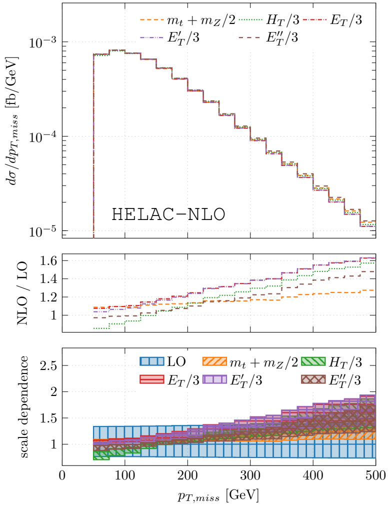
G.B, Hartanto, Kraus, Weber and Worek, arXiv:1907.09359 [hep-ph]



- $\mu = \mathbf{m_t + m_Z/2}$ $\rightarrow$ NLO gets outside LO uncertainties
- $\mu = \mathbf{H_T/3}, \mathbf{E_T/3}, \ldots$ $\rightarrow$ improved perturbative convergence!

Differential cross sections

An interesting case: p_T^{miss}



- Fixed scale behaves much better for p_T^{miss}: reduced shape distortions.

- It is not a threshold effect: the region $m_{t\bar{t}} \approx 2m_t$ is not ehanced in any special way

- Rather due to different kinematics of ν's originated from top or Z decays:

$$p_{T,Z} \equiv p_T(\nu_\tau + \bar{\nu}_\tau) \qquad p_T'^{miss} \equiv p_T(\nu_e + \bar{\nu}_\mu)$$

$$\langle p_T'^{miss} \rangle < \langle p_T^{miss} \rangle < \langle p_{T,Z} \rangle$$

$\hookrightarrow$ Dynamical scales (typically hard) work fine for $p_{T,Z}$ but not for $p_T'^{miss}$, which dominates the convolution

Summary

- We have achieved the first NLO predictions for off-shell $t\bar{t}Z$ production (dilepton channel) with **HELAC-NLO**
- Good theoretical control over $t\bar{t}Z$ is key for DM searches in $t\bar{t} + E_T^{miss}$: shapes, not only normalization!
- NLO is mandatory for good modeling of $t\bar{t}Z$ observables: differential K-factors are far from being constant
- Adopting judicious scales can improve perturbative stability and modeling of individual observables

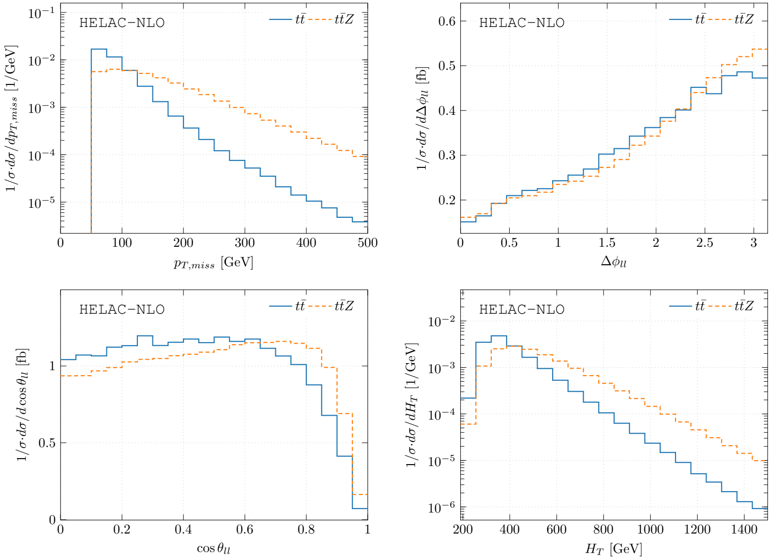
Outlook

- How good is modeling of top decays in **Madgraph5_aMC@NLO**?
- How important are the off-shell effects within the analysis considered?
- How much can one improve DM searches with more accurate modeling of SM backgrounds?

We are happy to share our $t\bar{t}Z$ Ntuples. If interested for your analysis, contact us!

Backup slides

Comparing $t\bar{t}$ and $t\bar{t}Z(Z \to \nu\bar{\nu})$ kinematics: distributions normalized to one



G.B, Hartanto, Kraus, Weber and Worek, arXiv:1907.09359 [hep-ph]