Irreducible backgrounds for Dark Matter searches at the LHC: $\mathrm{t\bar{t}Z(Z \to \nu\bar{\nu})}$

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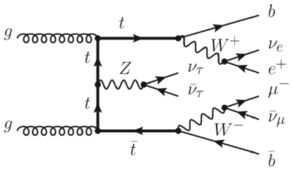
In collaboration with H. B. Hartanto, M. Kraus, T. Weber and M. Worek

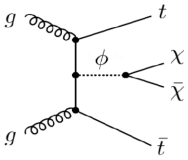
Based on JHEP **1911** (2019) 001 [arXiv:1907.09359 [hep-ph]]

Introduction

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



... having in mind a wider perspective: searches for **Dark Matter** (DM) in the channel $t\bar{t} + E_T^{miss}$



Motivation

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

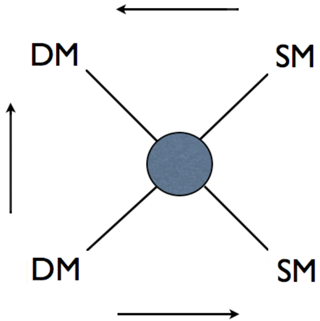
Collider searches

[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 ...

Motivation

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

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[underground nuclear recoil experiments]
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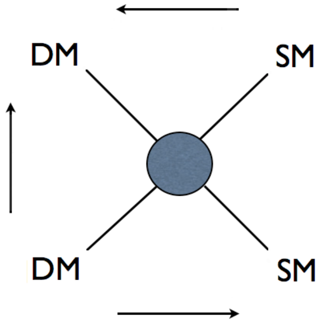


Our focus is on DM searches at **LHC**

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

Motivation

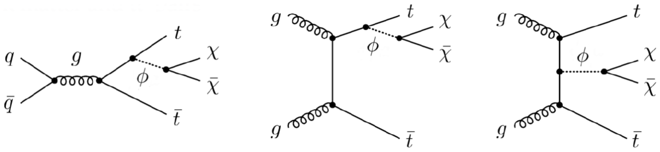
It is useful to study DM using *simplified models*:

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

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

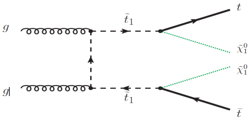
$\hookrightarrow$ in models with MFV, DM couples preferentially to top quarks

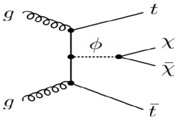


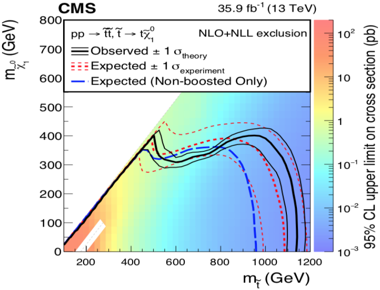
Arina *et al.*, arXiv:1605.09242 [hep-ph]
Haisch, Pani and Polesello, arXiv:1611.09841 [hep-ph]

Motivation

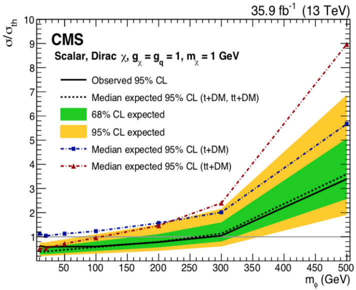
Recent examples of exclusion limits for SUSY or DM based on $t\bar{t} + E_T^{miss}$, interpreted in the context of simplified models







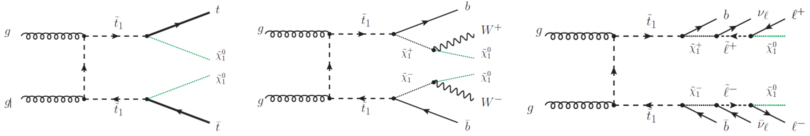
arXiv:1812.06302 [hep-ex]



arXiv:1901.01553v2 [hep-ex]

Motivation

Various theories also predict viable DM candidates (WIMP's), *e.g.* SUSY:



All these BSM processes share a typical signature: visible final states recoiling against large missing transverse energy (E_T^{miss})

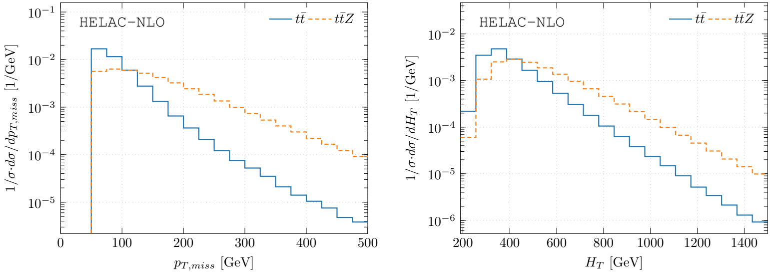
Various **SM backgrounds** can also resemble the same signature:

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

Motivation

While leading to the same *visible* final state, $t\bar{t}$ and $t\bar{t}Z(Z \to \nu\bar{\nu})$ exhibit different kinematics

[distributions normalized to one]



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

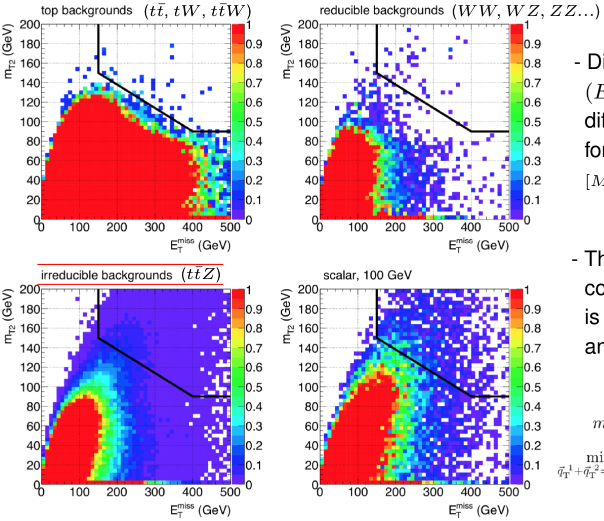
At the *inclusive* level, $t\bar{t}Z(Z \to \nu\bar{\nu})$ is suppressed by orders of magnitude with respect to $t\bar{t}$

$\hookrightarrow$ Is it important to strive for higher accuracy for such a small background? Yes!

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 DM 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

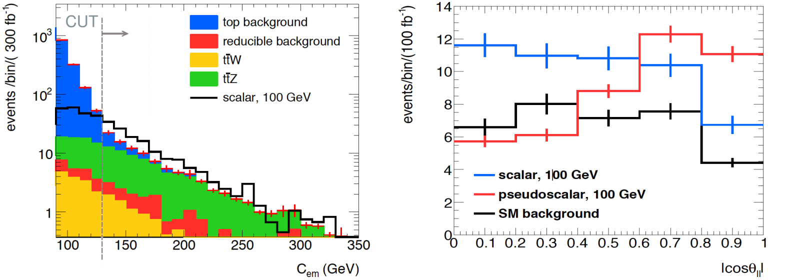
$$m_{\mathrm{T2}}^2(\vec{p}_{\mathrm{T}}^{\,\ell_i}, \vec{p}_{\mathrm{T}}^{\,\ell_j}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}) \equiv \min_{\vec{q}_{\mathrm{T}}^{\,1}+\vec{q}_{\mathrm{T}}^{\,2}=\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \left\{ \max \left[m_{\mathrm{T}}^2(\vec{p}_{\mathrm{T}}^{\,\ell_i},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

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]



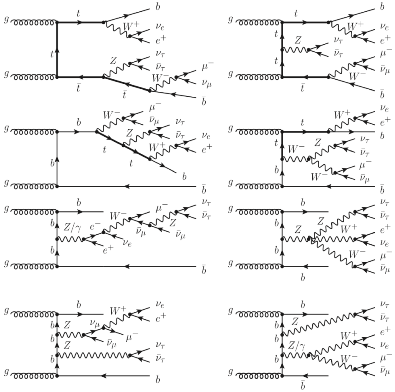
- With 300 fb^{-1}, assuming 20% systematics for SM backgrounds, it should be possible to resolve between the two CP hypotheses up to $M_\phi \approx 200$ GeV

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

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

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

- NLO QCD $\rightarrow$ stable tops
  Lazopoulos *et al.*, '08
- NLO QCD $\rightarrow$ NWA with NLO decays
  Röntsch and Schulze '14
- NLO+PS QCD
  Kardos, Garzelli and Trocsanyi '12
- NLO+PS 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

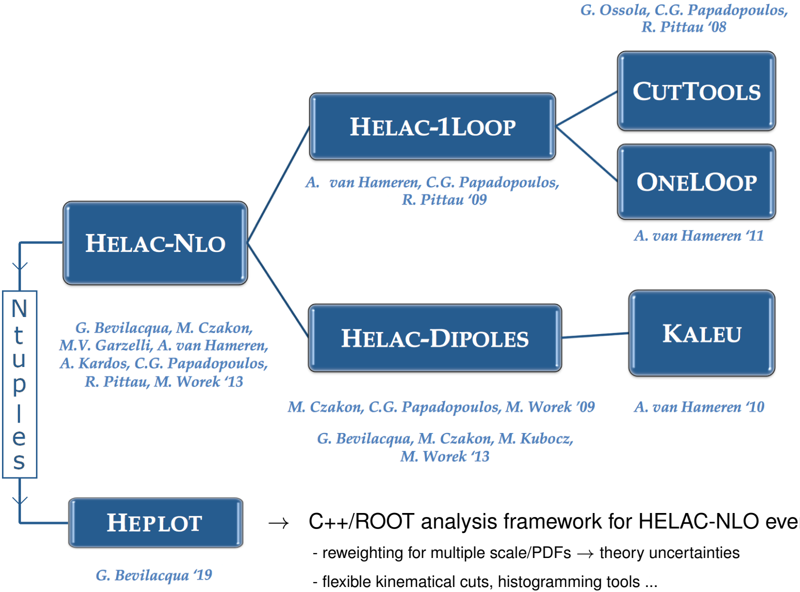


- In 1611.09841, $t\bar{t}Z$ events are generated with **Madgraph5_aMC@NLO** at LO and then normalized with the NLO cross section (*on-shell* top decays)

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

We have performed the first complete *off-shell* NLO calculation (dilepton channel) with **HELAC−NLO**

The HELAC-NLO framework



→ C++/ROOT analysis framework for HELAC-NLO events

- reweighting for multiple scale/PDFs → 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:

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

$\to$ **Fixed** and **dynamical** scales, either ”resonant aware” (E_T, E_T', E_T'') or ”blind” (H_T)

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

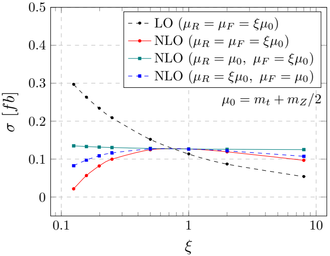
$$m_{T,i} = \sqrt{p_{T,i}^2 + m_i^2}$$

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%



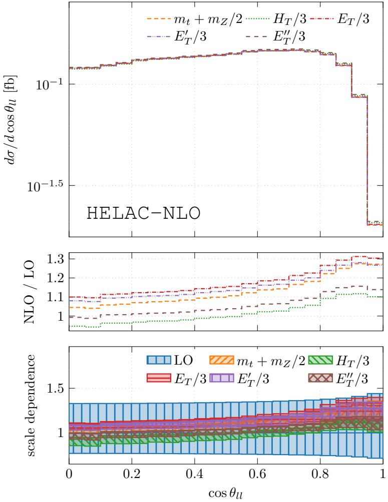
- Complete cross section for dilepton channel (e/μ) can be realized by multiplying results by 12:

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

- Scale uncertainties $\sim \mathcal{O}(5-7\%)$
- PDF uncertainties $\sim \mathcal{O}(3\%)$

Differential cross sections

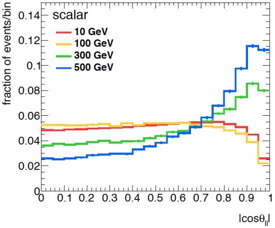
G.B, Hartanto, Kraus, Weber and Worek, arXiv:1907.09359 [hep-ph]



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

- Sensitive to the nature of DM mediator

Haisch *et al.* '16



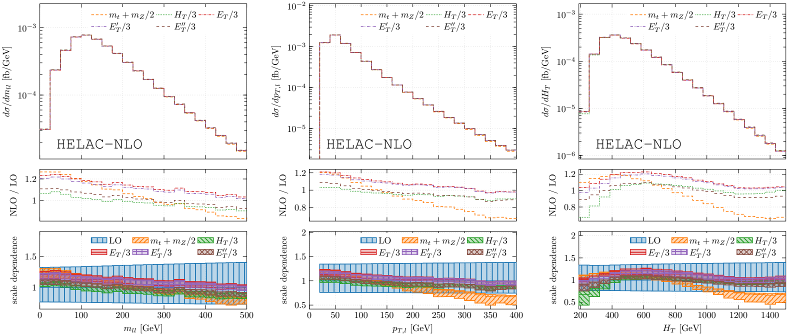
- Differential K-factors far from constant!
  - $\mu = m_t + m_Z/2$: $+4\% \leftrightarrow 27\%$
  - $\mu = H_T/3$: $-5\% \leftrightarrow 10\%$
  - $\mu = E''_T/3$: $-1\% \leftrightarrow 14\%$

Differential cross sections

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

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

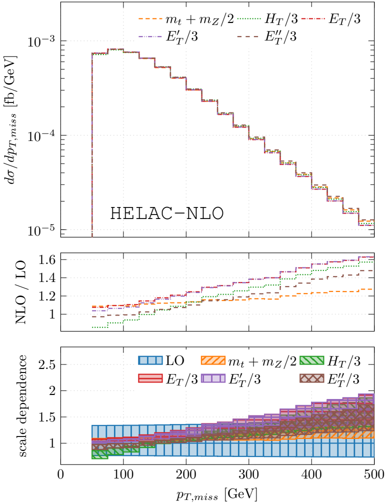
dilepton inv. mass | charged lepton's p_T | transverse energy (H_T)



- $\mu = \mathbf{m_t + m_Z/2}$ → NLO gets outside LO uncertainties
- $\mu = \mathbf{H_T/3, E_T/3}, \ldots$ → 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 first NLO predictions for off-shell $t\bar{t}Z(Z \to \nu\bar{\nu})$ production (dilepton channel) with **HELAC-NLO**
- NLO is mandatory for a proper modeling of most $t\bar{t}Z$ observables. Differential K-factors are far from being constant: shapes are important, not only normalization
- Adopting judicious scales improves perturbative stability and the modeling of individual observables

Outlook

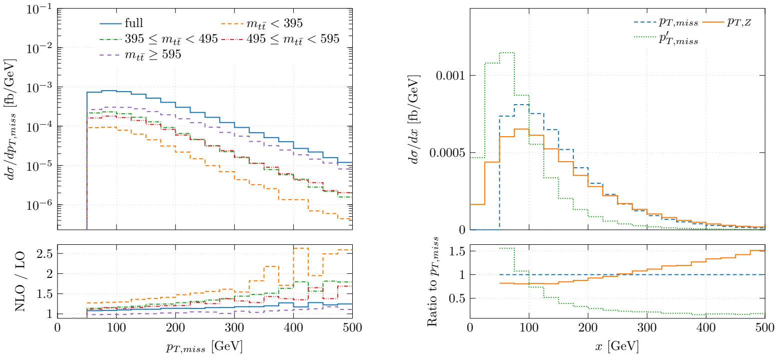
- How important is accurate modeling of top decays and off-shell effects?

  $\hookrightarrow$ NEW: NWA with radiative decays implemented in **HELAC-NLO**! Systematic comparisons underway ... arXiv:1912.09999 [hep-ph]
- How much can DM searches improve by use of more accurate SM backgrounds?

Our results are available in the form of event Ntuples. If interested, contact us

Backup slides

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



$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\nu_\tau\bar{\nu}_\tau + X$$

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