Search for an invisible scalar in $t\bar{t}$ final states at the LHC

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Find out more: JHEP11(2023)125

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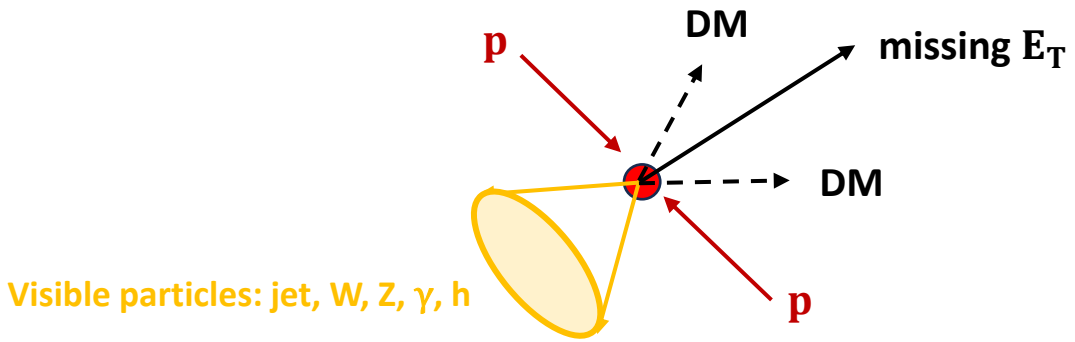
Introduction

- **Dark matter (DM) searches at colliders** are a key component of DM detection experiments. **Collider signature:** excess of events in final state objects recoiling against **large amounts of missing transverse energy ($\mathbf{E_T}$)**. **Mono-X searches** (mono-jet, mono-V, mono-Higgs) have been the main focus at the LHC.



- Searches for DM produced with a $t\bar{t}$ pair ($\mathbf{pp \rightarrow t\bar{t} + missing\ E_T}$), mostly using missing energy as a discriminator, have also been considered.

Haisch et al. – 1611.09841, 1812.00694, 2107.12389, Hermann, Worek - 2108.01089

- Our goal is to **look for very light particles hidden in the on-going $t\bar{t}$ searches and analyses**, produced with a $t\bar{t}$ pair that can decay to DM. For this we apply an experimental-like $pp \rightarrow t\bar{t}$ analysis (dileptonic final state) to $pp \rightarrow t\bar{t}Y_{0,1}$, with $\mathbf{Y_{0,1}}$ **a new spin-0,1 DM mediator.**

- **We fully reconstruct the $t\bar{t}$ system, without trying to reconstruct the mediator**. Does this particle change any **$t\bar{t}$ distributions**? Can the analysis be used to set **limits on the mediators couplings and mass**? Can we **distinguish mediators with different spins and CP-natures**?

DM Lagrangian

- Analysis performed within the context of **simplified models of DM production** at the LHC. The ***DMsimp*** model was used.

Spin-0 DM mediator (Y_0)

$$\mathcal{L}_{SM}^{Y_0} = \frac{y_{33}^t}{\sqrt{2}}\bar{t}(g_{u33}^S + ig_{u33}^P\gamma^5)tY_0$$

$$\mathcal{L}_{Y_0}^{X_D} = \bar{X}_D(g_{X_D}^S + ig_{X_D}^P\gamma^5)X_D Y_0$$

- **CP-even:** $g_{u33}^S = 1, g_{u33}^P = 0.$
- **CP-odd:** $g_{u33}^S = 0, g_{u33}^P = 1.$
- **Scalar-mixed:** $g_{u33}^{S/P} \neq 0.$

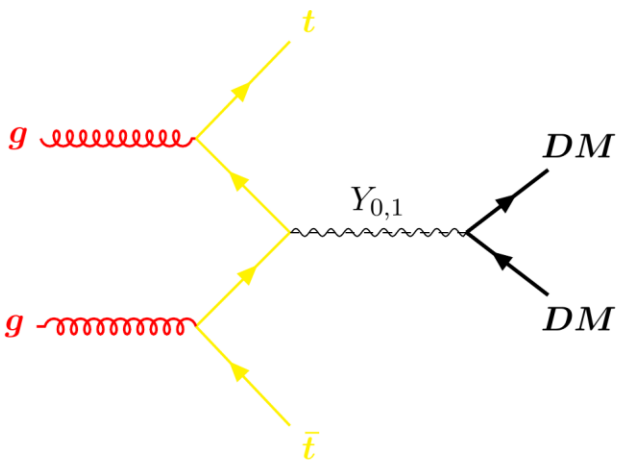
Spin-1 DM mediator (Y_1)

$$\mathcal{L}_{SM}^{Y_1} = \bar{t}\gamma_\mu(g_{u33}^V + g_{u33}^A\gamma_5)tY_1$$

$$\mathcal{L}_{Y_1}^{X_D} = \bar{X}_D\gamma_\mu(g_{X_D}^V + g_{X_D}^A\gamma^5)X_D Y_1^\mu$$

- **Vector:** $g_{u33}^V = 0.25, g_{u33}^A = 0.$
- **Axial-vector:** $g_{u33}^V = 0, g_{u33}^A = 0.25.$
- **Vector-mixed:** $g_{u33}^{V/A} \neq 0.$

Backovic et al. – 1508.05327



- **Dileptonic final state:** $t\,(\bar{t}) \rightarrow W^+b\,(W^-\bar{b})$ and $W^+(W^-) \rightarrow l^+\upsilon_l(l^-\bar{\upsilon}_l)$, with $l = e, \mu$.
- $\mathbf{BR(Y_{0,1} \rightarrow X_D\bar{X}_D) = 1}$ → we focus only on the tops and mediator interaction.

Event generation, selection and kinematic reconstruction

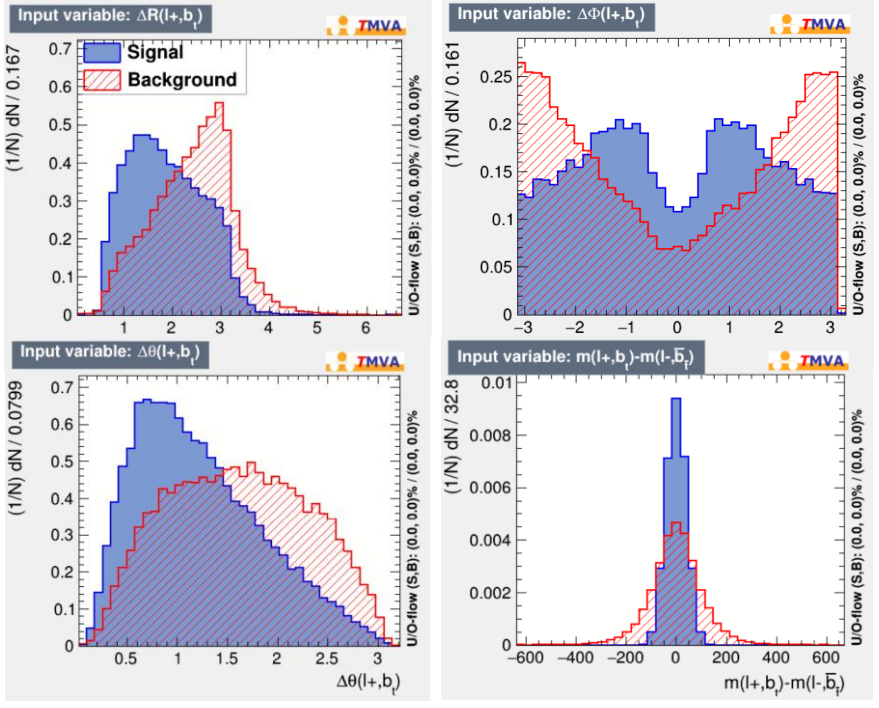
- LHC-like signal and background events generated with ***MadGraph5_aMC@NLO***, for a CM energy of 13 TeV. ***DMsimp*** used to generate $\mathbf{pp \rightarrow t\bar{t}Y_0}$ **signal events** at LO for both pure scalar and pseudo-scalar mediators, with m_{Y_0} = 0, 1, 5, 10, 125 GeV (**similar for the spin-1 case, with m_{Y_1} = 5 GeV**). Alwall, Herquet, Maltoni, Mattelaer, Stelzer – 1106.0522

- **Most significant backgrounds**: $t\bar{t}$ +3 jets, $t\bar{t}V$ + 1 jet, $t\bar{t}H$, single top, V + 4 jets, $Vb\bar{b}$ + 2 jets, VV (V = W, Z). ***Pythia*** used for showering and hadronization. ***DELPHES*** used for a fast simulation of an LHC-like detector.

- **Selection cuts:**
  - $N_{jets} \geq 2$ and $N_{lep} \geq 2$
  - $p_T > 20$ GeV and $|\eta| < 2.5$
  - $|m_{l^+l^-} - m_Z| > 10$ GeV and 2 b-jets

- We use **multivariate statistical methods** from the Toolkit for Multivariate Data Analysis – *TMVA* - to **assign the reconstructed jets** to the correct b-quarks from the associated top quarks.

- **Several distributions used to train and test these methods:**
  - ΔR, $\Delta\phi$, $\Delta\theta$, m^{inv} of pairs (b_t, l^+), $(\bar{b}_{\bar{t}}, l^-)$.



Event generation, selection and kinematic reconstruction

- **3-momentum of the undetected neutrinos** reconstructed by imposing **energy-momentum conservation conditions**. If several solutions exist, a likelihood function is built using parton level information and the solution with the highest likelihood is picked.

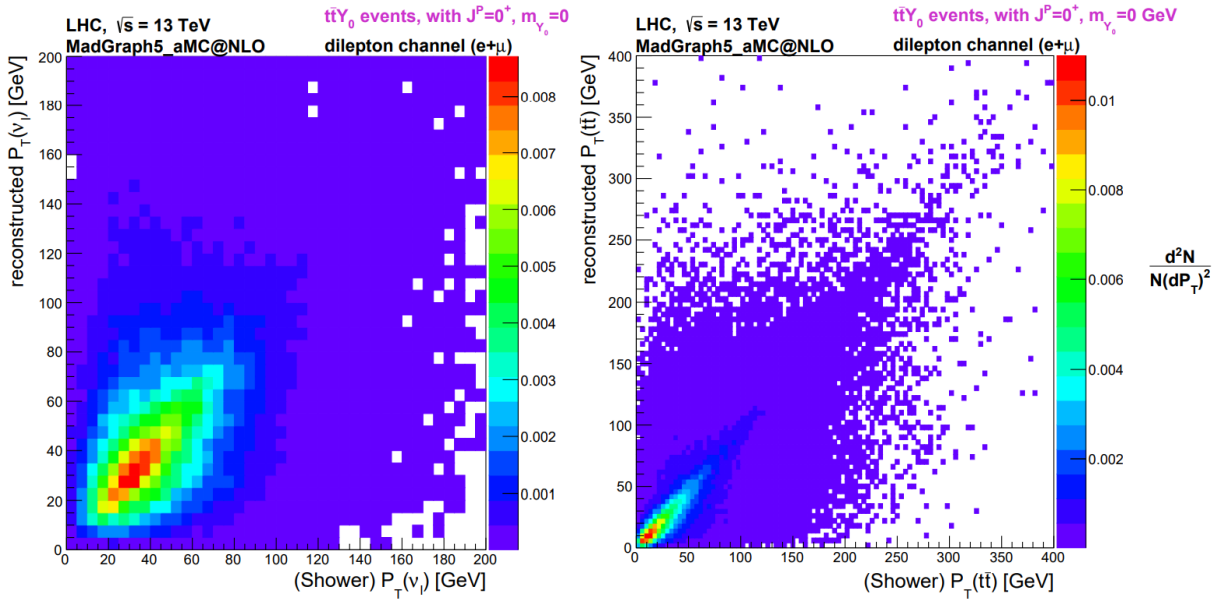
$$
\begin{aligned}
(p_\nu + p_{\ell^+})^2 &= m_W^2, \\
(p_{\bar{\nu}} + p_{\ell^-})^2 &= m_W^2, \\
(p_{W^+} + p_b)^2 &= m_t^2, \\
(p_{W^-} + p_{\bar{b}})^2 &= m_{\bar{t}}^2,
\end{aligned}
\qquad
\begin{aligned}
p_\nu^x + p_{\bar{\nu}}^x &= \not{E}^x, \\
p_\nu^y + p_{\bar{\nu}}^y &= \not{E}^y,
\end{aligned}
$$

$$
L \propto \frac{1}{p_{T_\nu} p_{T_{\bar{\nu}}}} P(p_{T_\nu}) P(p_{T_{\bar{\nu}}}) P(p_{T_t}) P(p_{T_{\bar{t}}}) P(p_{T_{t\bar{t}}})
$$

- **Total missing transverse energy is fully accounted for by the neutrinos** (negligible DM mediator contribution!).
- For a massless spin-0 DM mediator, the efficiency of the reconstruction is similar to $t\bar{t}$ analyses.

Implications:

- **Reconstructed kinematics allows to study the impact of new light invisible particles in the $t\bar{t}$ angular distributions.**
- **A typical $t\bar{t}$ analysis cannot eliminate these events!**

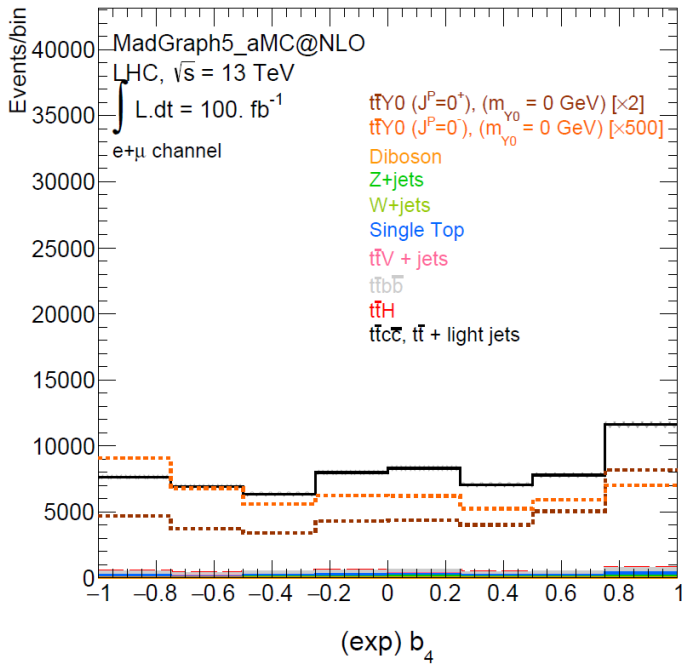


Strong correlation between parton level and reconstructed kinematics

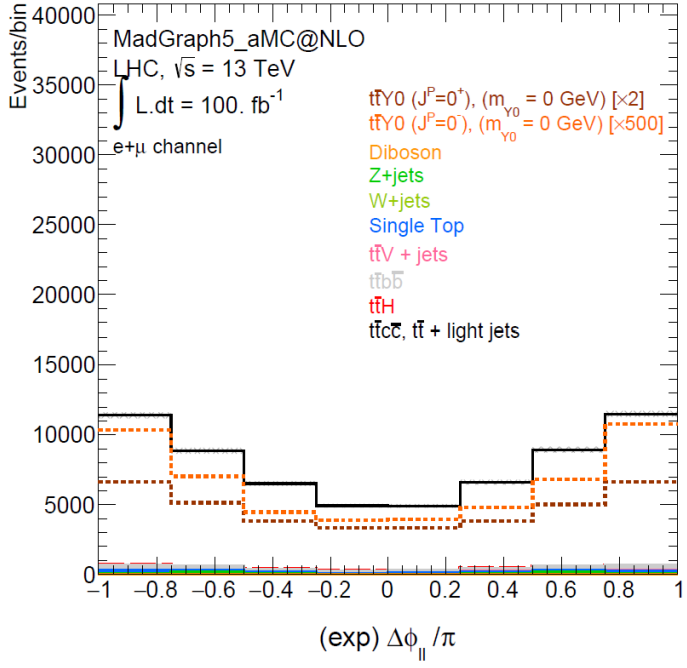
Azevedo, Capucha, Gouveia, Onofre, Santos - 2003.09043, 2012.10730, 2208.04271

Results

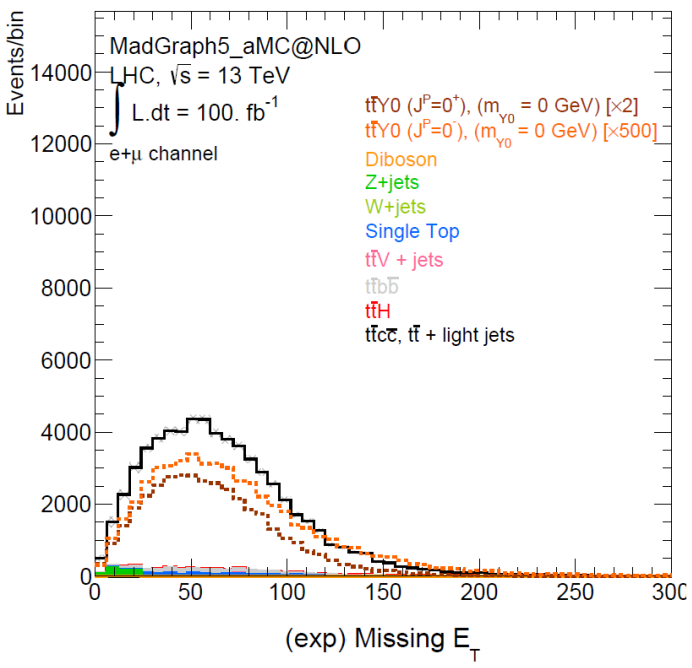
$$b_4 = (p_t^z \cdot p_{\bar{t}}^z)/(|\vec{p}_t| \cdot |\vec{p}_{\bar{t}}|)$$



Δϕ$_{l+l-}$



missing ET



- **Differences in the shapes of the SM background, CP-even and CP-odd angular distributions** can be observed due to the presence of the spin-0 mediator.

- The **missing transverse energy** distribution shows a quite similar behaviour for the SM background, and both CP-even and CP-odd signals. Thus, it is **not a good discriminating variable** to look for light DM in $t\bar{t}$ final states.

Results

- **Confidence level (CL) limits for the DM mediator couplings** were set, using the **$\Delta\phi_{l^+l^-}$ and b_4 distributions**, for different masses. **Fixed LHC luminosities** of 200 fb^{-1} and 3000 fb^{-1} (High-Luminosity LHC).

- **Two different exclusion scenarios** are considered:

  - **Scenario 1: if no new particle is found, what are the exclusion limits we can set?**
    - exclusion of the SM + new scalar-mixed DM mediator (H_1), assuming the SM as null hypothesis (H_0)

Scalar-mixed cross-section:

$$\sigma_{\text{scalar-mixed}} = (g^S_{u33})^2\,\sigma_{\text{CP-even}} + (g^P_{u33})^2\,\sigma_{\text{CP-odd}}$$

  - **Scenario 2: if a new particle is found, would we be able to test its properties (CP, spin)?**
    - exclusion of the SM + new vector + new CP-odd DM mediators (H_1), assuming the SM + vector DM mediator as null hypothesis (H_0)

Results – scenario 1

- **Identical exclusions limits for both observables**. Similar results obtained when using a simple counting experiment: **observable choice has little to no impact on the exclusion limits in this scenario.**

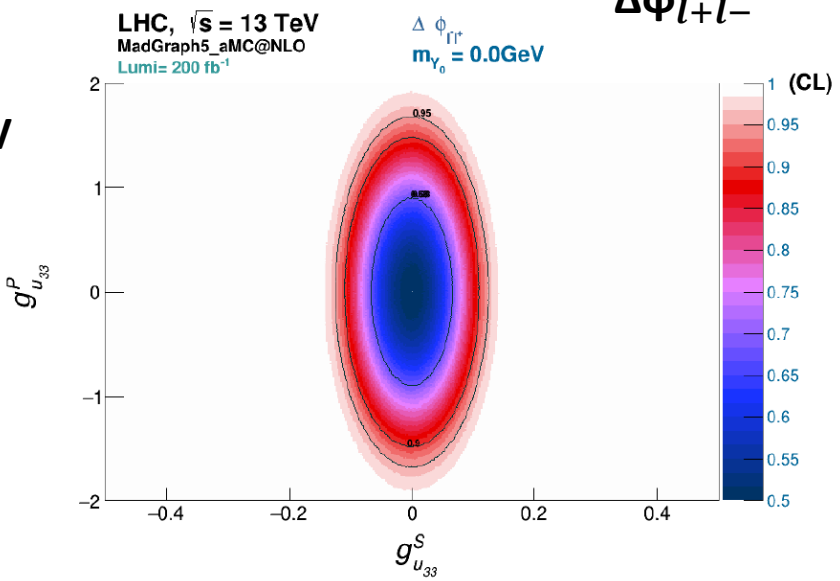
L = 200 fb^{-1}

m_{Y_0} = 0 GeV

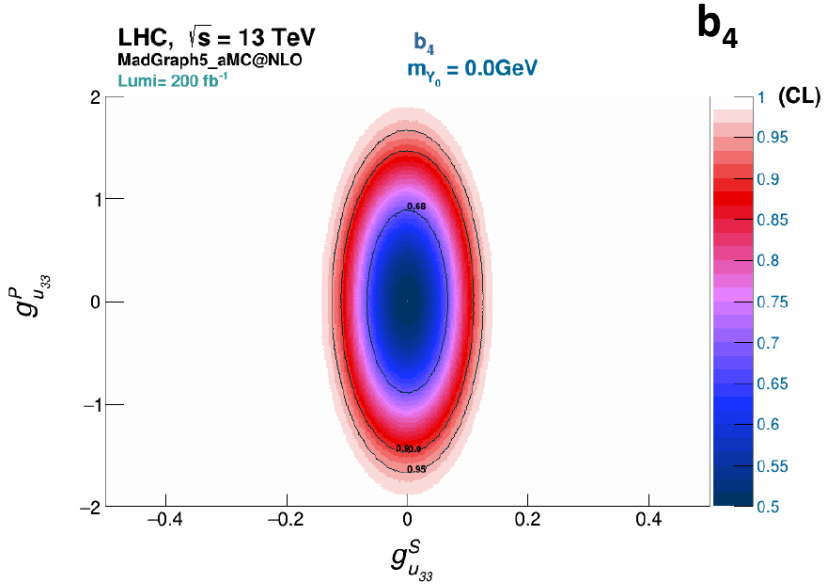
H_0 = SM

H_1 = SM + $Y_{0(\mathrm{scalar-mixed})}$

$\Delta\phi_{l+l-}$



b_4

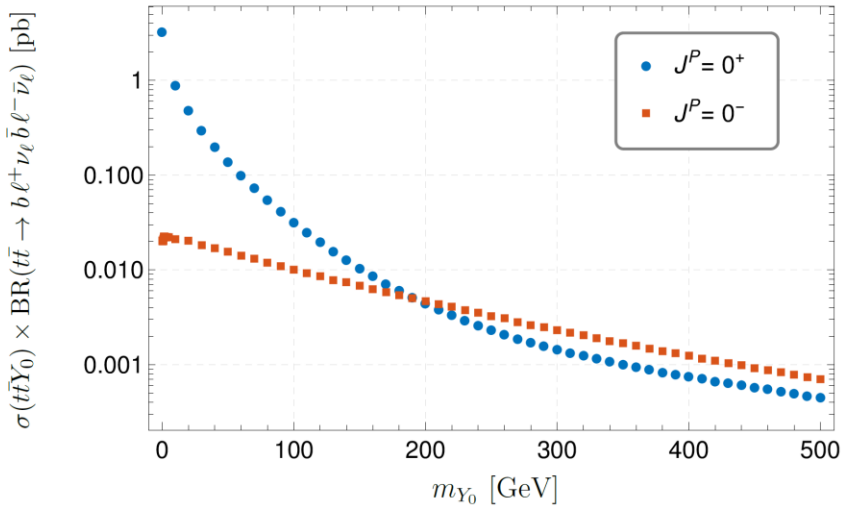


Exclusion Limits from $\Delta\phi_{l+l-}$		$L = 200$ fb^{-1} (68% CL)	$L = 200$ fb^{-1} (95% CL)	$L = 3000$ fb^{-1} (68% CL)	$L = 3000$ fb^{-1} (95% CL)
$m_{Y_0} = 0$ GeV	$g^S_{u33} \in$	[-0.067, +0.067]	[-0.125, +0.125]	[-0.022, +0.022]	[-0.052, +0.052]
	$g^P_{u33} \in$	[-0.91, +0.91]	[-1.71, +1.71]	[-0.44, +0.44]	[-0.85, +0.85]

Results – scenario 1

H_0 = SM

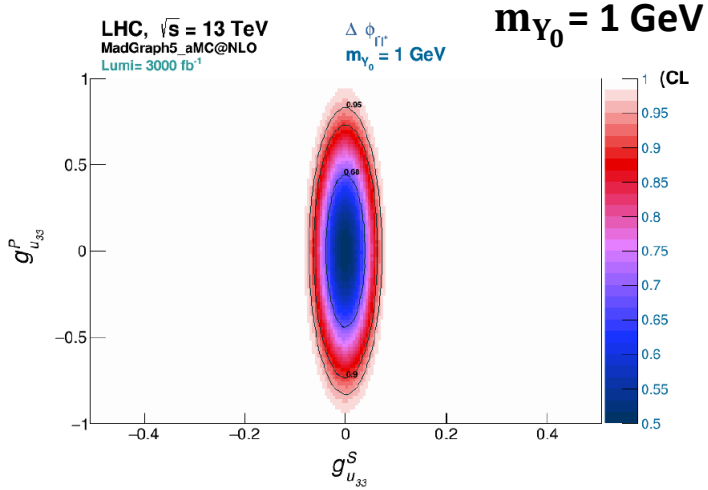
H_1 = SM + $Y_{0(\mathrm{scalar-mixed})}$



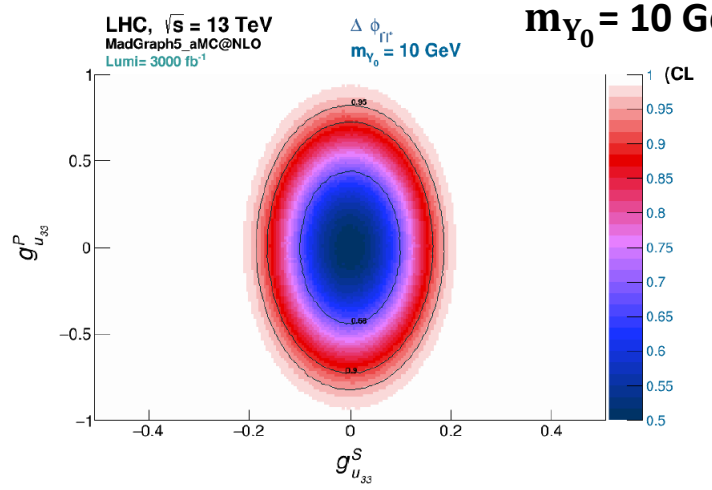
Exclusion limits worsen as masses increase, since the $t\bar{t}Y_0$ production cross section decreases for heavier Y_0 masses.

High-Luminosity LHC (3000 fb^{-1})

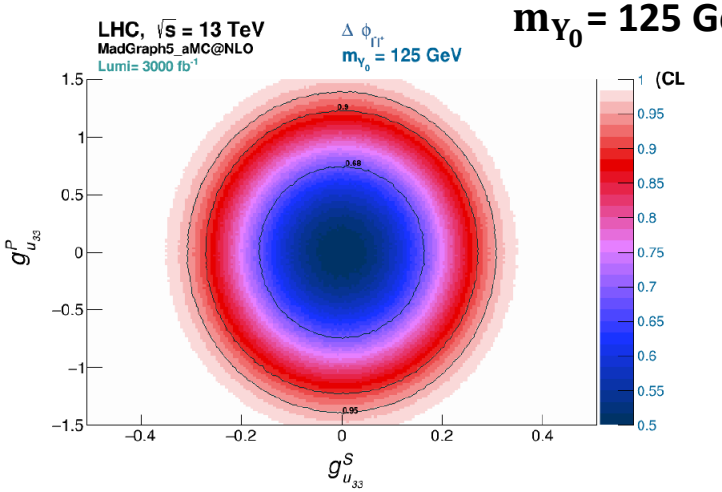
m_{Y_0} = 1 GeV



m_{Y_0} = 10 GeV



m_{Y_0} = 125 GeV



Results – scenario 2

L = 200 fb^{-1}

H_0 = SM + $Y_{1(\text{vector})}$

H_1 = SM + $Y_{1(\text{vector})}$ + $Y_{0(\text{CP-odd})}$

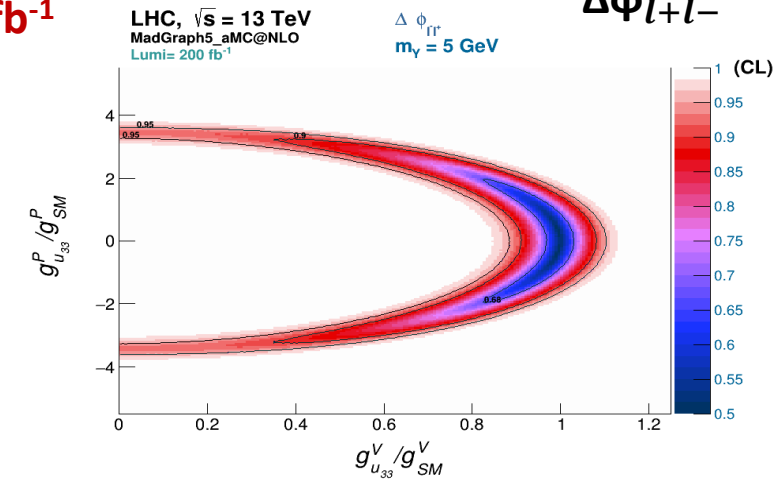
$m_{Y_{0,1}}$ = 5 GeV

$g^P_{SM} = 1$

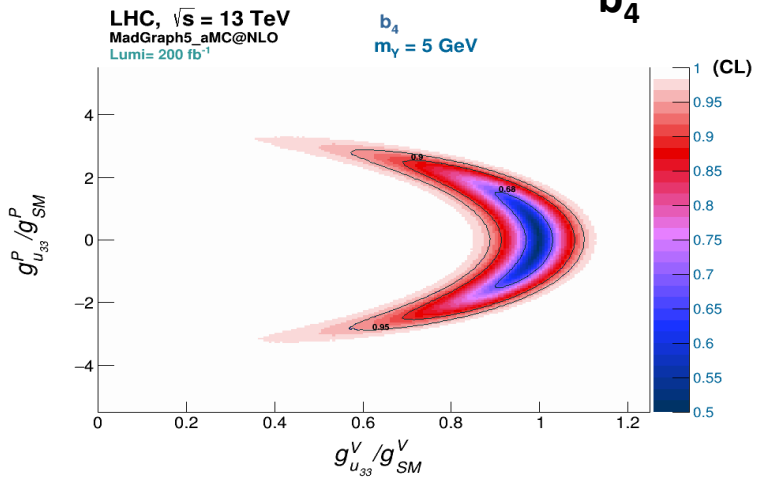
$g^V_{SM} = 0.25$

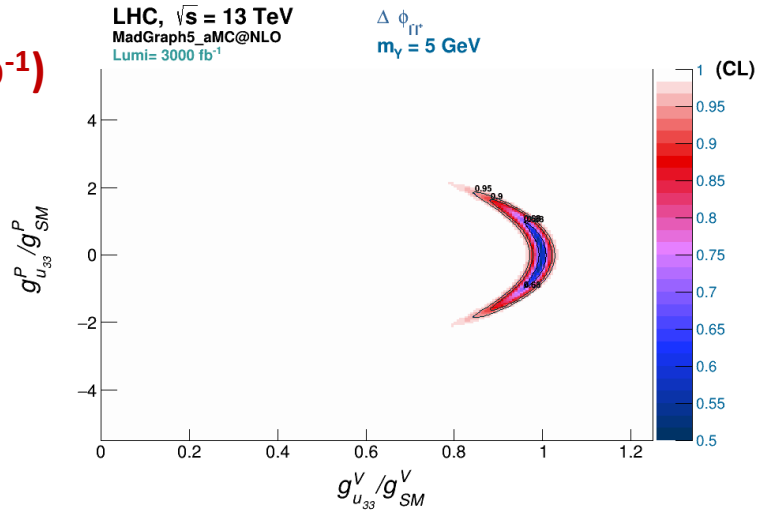
High-Luminosity LHC (3000 fb^{-1})

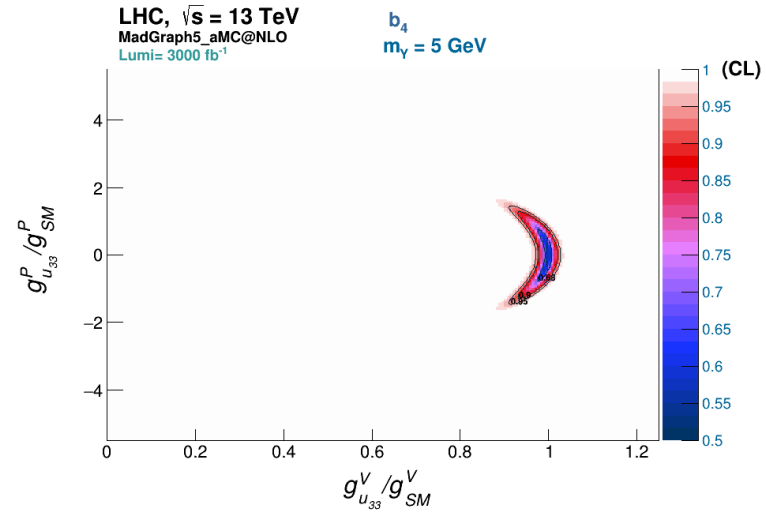
$\Delta\phi_{l^+l^-}$



b_4







- **Using spin observables will play a crucial role** to determine the CP-nature and spin of DM mediators upon discovery.

Conclusions

- **The reconstruction of $t\bar{t}$ systems cannot remove events where new particles are produced with a $t\bar{t}$ pair, in particular light bosons which can couple to DM.**

- **The presence of these new particles can change spin/angular observables in the $t\bar{t}$ systems.**

- **We should use these angular observables, which are sensitive to different mass scales, spins and CP-natures, to probe invisible sectors that could be hidden in $t\bar{t}$ events. Searching for events with large missing transverse energy may not be enough.**

THE END
THANK YOU!

Results – scenario 2.1

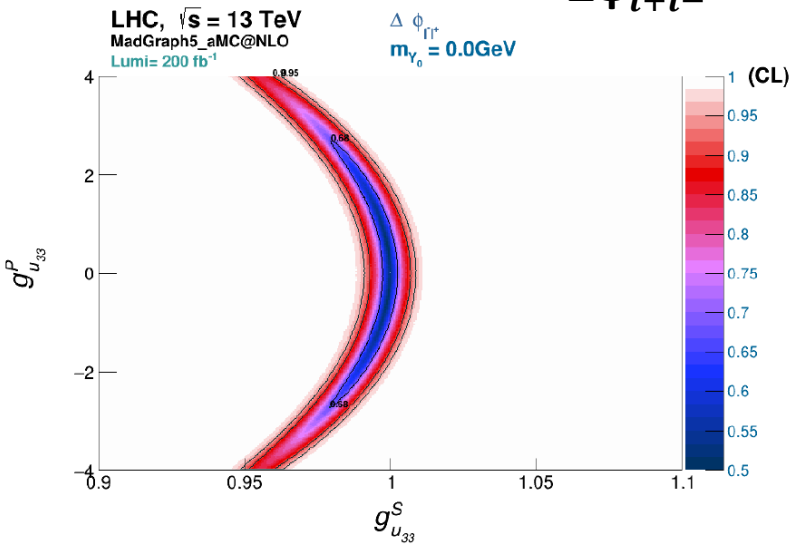
L = 200 fb^{-1}

m_{Y_0} = 0 GeV

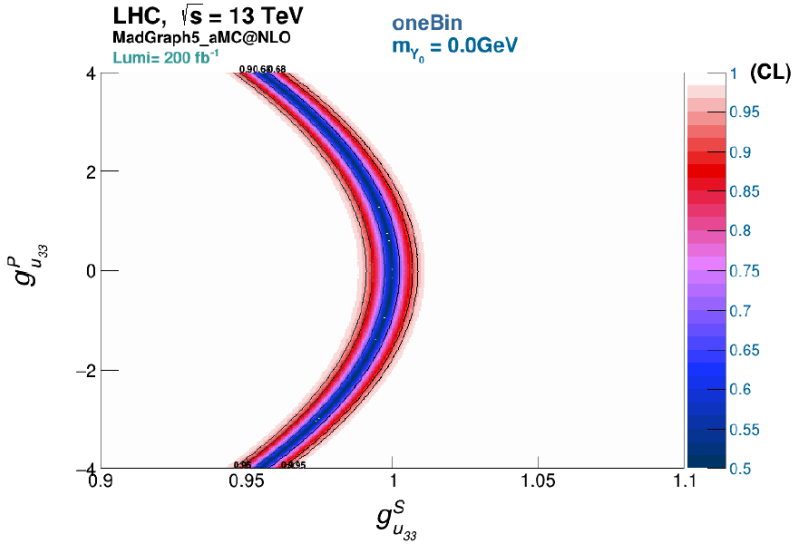
H_0 = SM + $Y_{0(CP-even)}$

H_1 = SM + $Y_{0(scalar-mixed)}$

$\Delta\phi_{l^+l^-}$

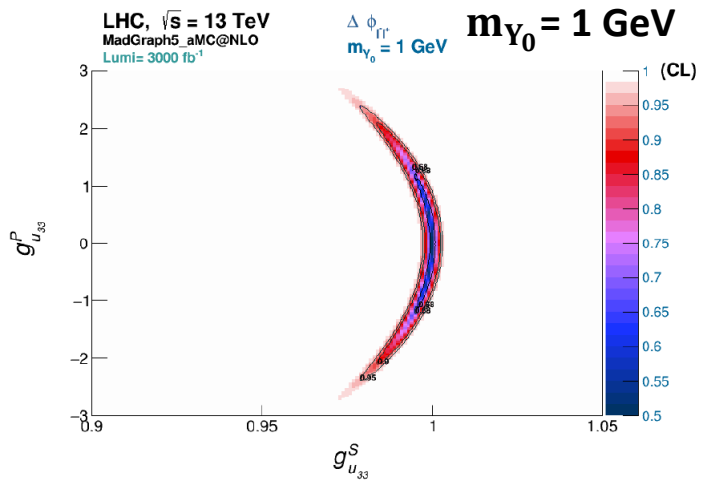


cross section measurement

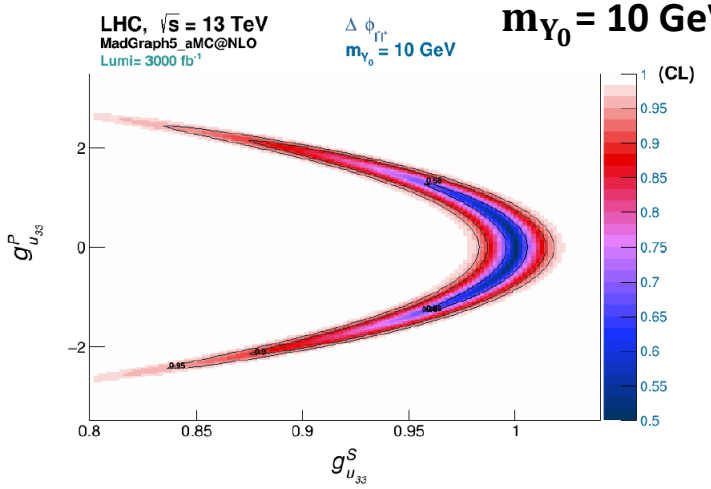


High-Luminosity LHC (3000 fb^{-1})

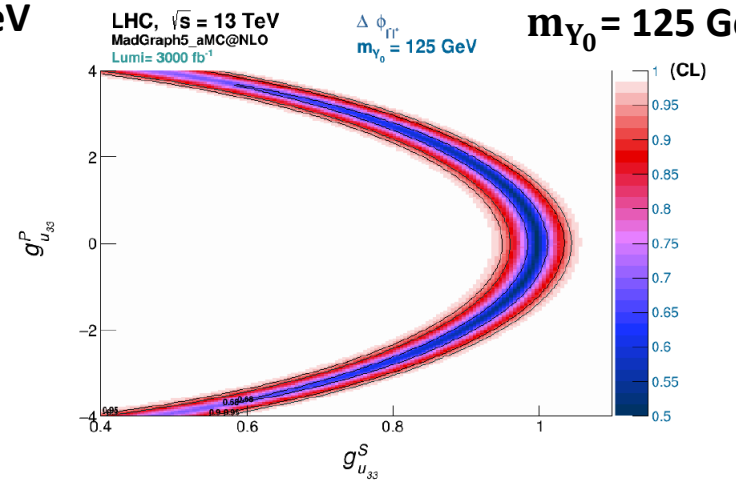
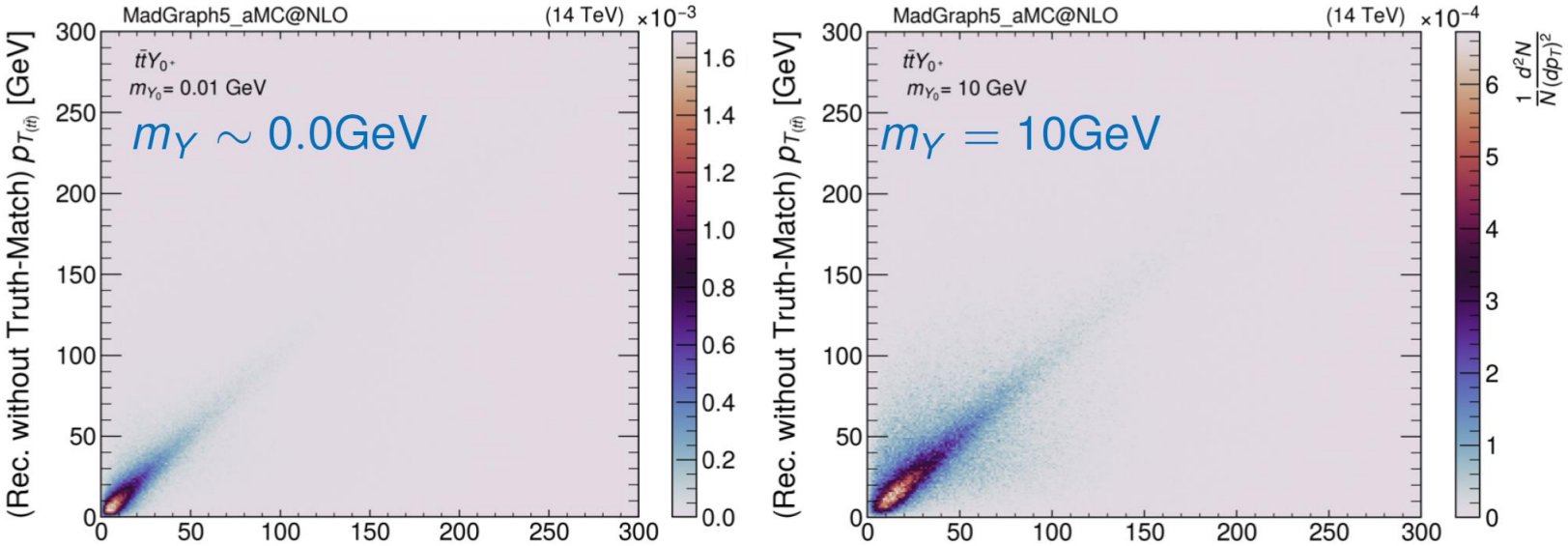
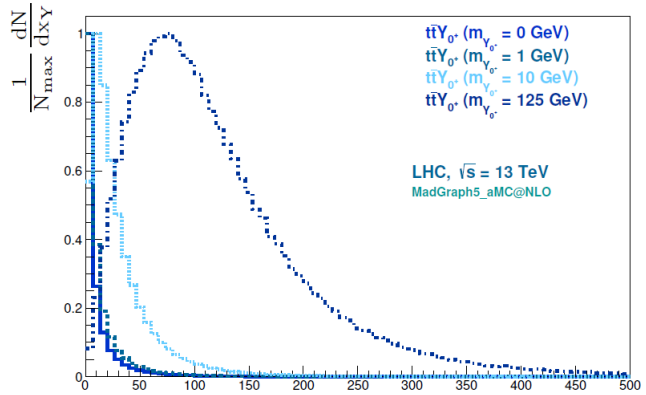
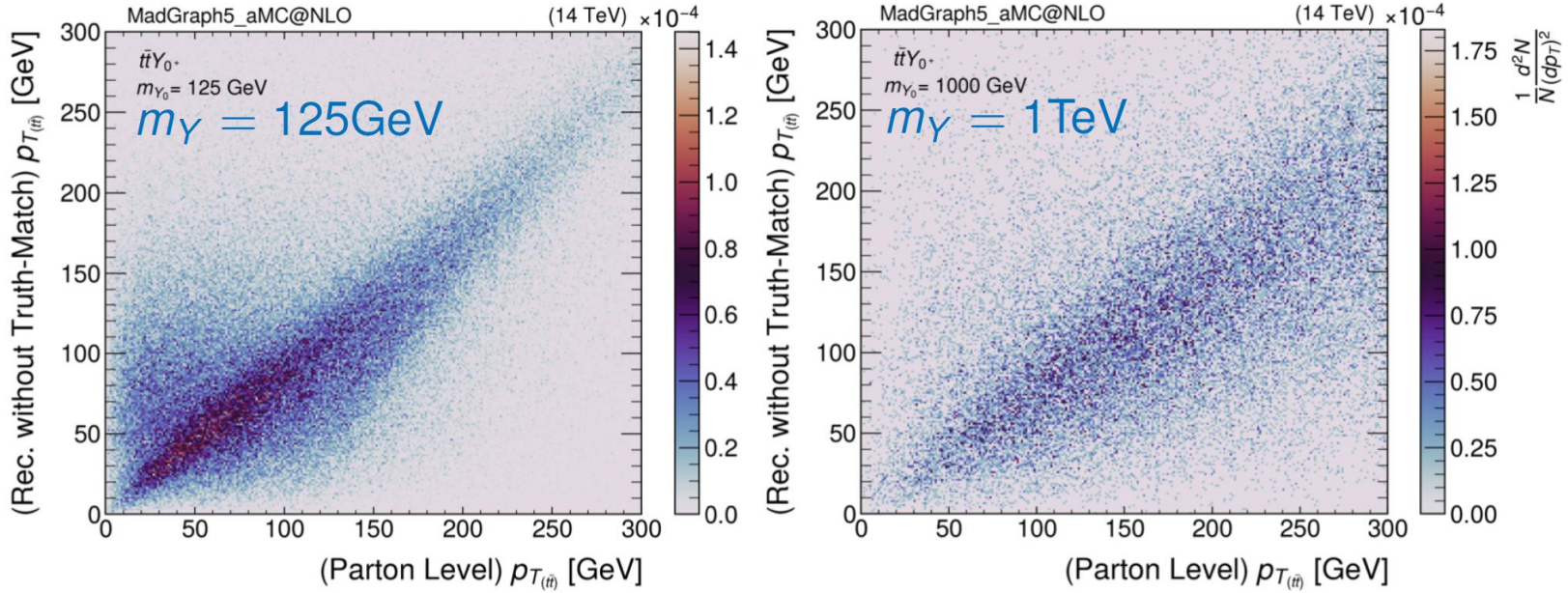
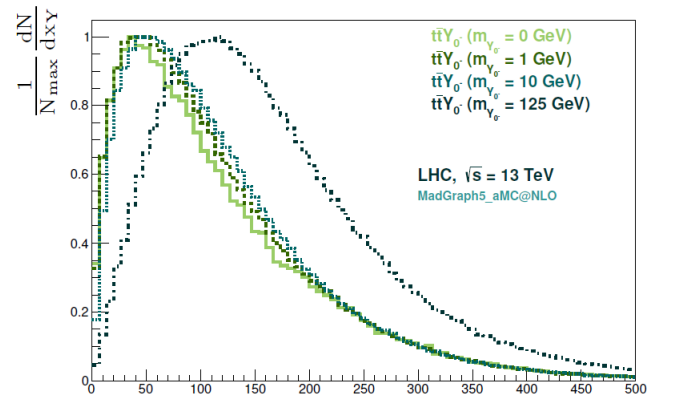
m_{Y_0} = 1 GeV



m_{Y_0} = 10 GeV



m_{Y_0} = 125 GeV



Kinematic reconstruction for heavier mediators