FCT Fundação para a Ciência e a Tecnologia

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

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Find out more: arXiv:2308.00819

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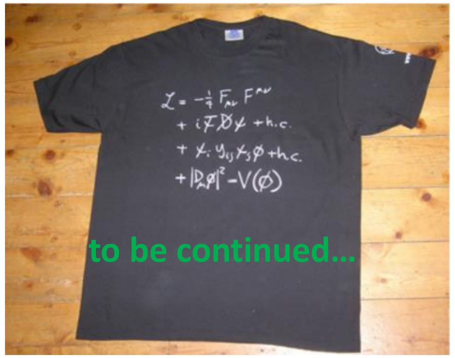
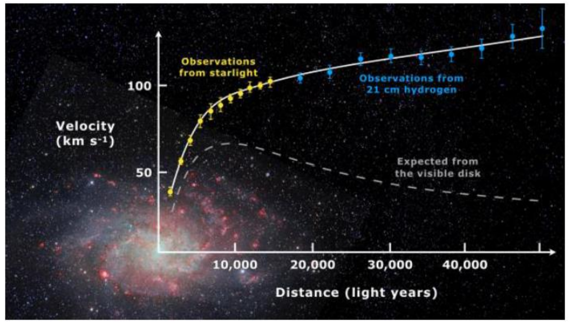
Introduction

In 2012, a **new scalar particle with a mass close to 125 GeV**, later identified as the **Higgs boson**, was discovered at the Large Hadron Collider (LHC), thus completing the **Standard Model (SM)** of particle physics. Only spin-0 particle (so far!).

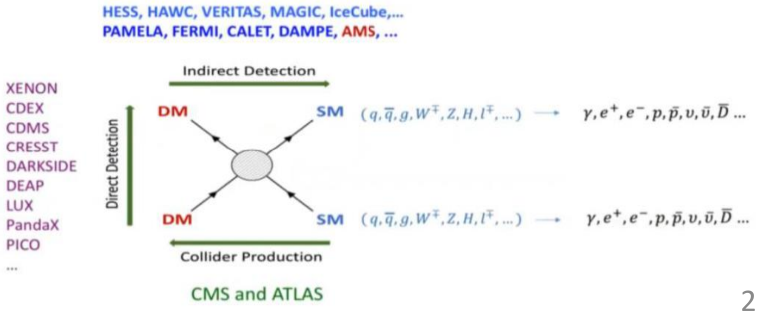
Most experimental results agree with the SM, with very few exceptions. But the **SM cannot be the final theory** – no viable candidate for **dark matter (DM)**, not enough CP-violation to explain **matter-antimatter asymmetry**, among others. **New physics beyond the SM** is necessary.





Evidence for the existence of dark matter (gravitational lensing effects, galactic rotational velocity curves, bullet Cluster) is by now **overwhelming**. However, its nature remains a mystery.

DM can be a new particle yet to be discovered. **Experimental efforts to detect DM** via direct detection (DD), indirect detection (ID) and collider searches have been **unsuccessful so far**.



Introduction

- **DM searches at colliders are a key component of DM detection experiments**. To be sensitive to DM at a collider, look for an excess of events in final state objects recoiling against **large amounts of missing transverse energy** ($\not{E}_T$). **Searches at the LHC** have mainly focused on **mono-event signatures** (mono-jet, mono-Higgs, others). Bounds also from the **Higgs invisible branching ratio.**

ATLAS – 2301.10731, DOI:10.22323/1.390.0658, CMS – DOI:10.22323/1.414.0260, PoS ICHEP2020 070

- Searches for DM particles produced alongside a $t\bar{t}$ pair $(\mathbf{pp \to t\bar{t} + \not{E}_T})$, mostly using missing energy as a discriminator, with **no attempt to reconstruct the kinematics of the top quarks**, have also been considered.

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

- Our goal is to **look for DM particles hidden in the on-going $t\bar{t}$ searches**, in particular **very light particles** (0 up to a few GeV in mass) produced with a $t\bar{t}$ pair. We consider a **new spin-0 DM mediator**, Y_0, that **couples to both DM and SM particles**, and apply the experimental analysis of $pp \to t\bar{t}$ (in the dileptonic final state) to $pp \to t\bar{t}Y_0$, to gauge the impact of this mediator.

- **Very clean final state**, directly **sensitive to the CP-nature of the mediator couplings** with the top quarks. Contrary to previous studies, we **fully reconstruct the $t\bar{t}$ system, without attempting to reconstruct the mediator**. If no differences are found in any distributions, can we set limits on the mediator Yukawa couplings as a function of its mass?

DM Lagrangian and CP-observables

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

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

Backovic et al. – 1508.05327

$$\mathcal{L}_{X_D}^{Y_0} = \bar{X}_D (g_{X_D}^S + i g_{X_D}^P \gamma_5) X_D \, Y_0$$

- **CP-even:** g_{u33}^S= 1, g_{u33}^P= 0. **CP-odd:** g_{u33}^S= 0, g_{u33}^P= 1. **CP-mixed:** $g_{u33}^{S/P} \neq 0$ (**CP-violating interaction**).
- t ($\bar{t}$) → $W^+ b$ ($W^- \bar{b}$) and $W^+ (W^-) \rightarrow l^+ \upsilon_l (l^- \bar{\upsilon}_l)$: **dileptonic final state**, with $l = e, \mu$.
- $\mathbf{BR\ (Y_0 \rightarrow X_D \bar{X}_D) \approx 1}$. We focus only on the tops and mediator interaction.

- **Several observables** have been proposed to **probe the CP-nature of the Higgs** in the Higgs-top couplings. To illustrate our findings, we considered the **azimuthal angle difference of the charged leptons** from the tops decay, $\boldsymbol{\Delta\phi_{l+l-}}$, and the $\mathbf{b_4}$ **variable** in the laboratory frame (LAB)

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

Gunion, He - hep-ph/9602226,
Buckley, Gonçalves - 1511.06451

- In order to evaluate this variable, the kinematic reconstruction of the $t\bar{t}$ system needs to be accomplished.

Event generation, selection and kinematic reconstruction

- LHC-like signals 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, 10, 125 GeV.

Alwall, Herquet, Maltoni, Mattelaer, Stelzer – 1106.0522

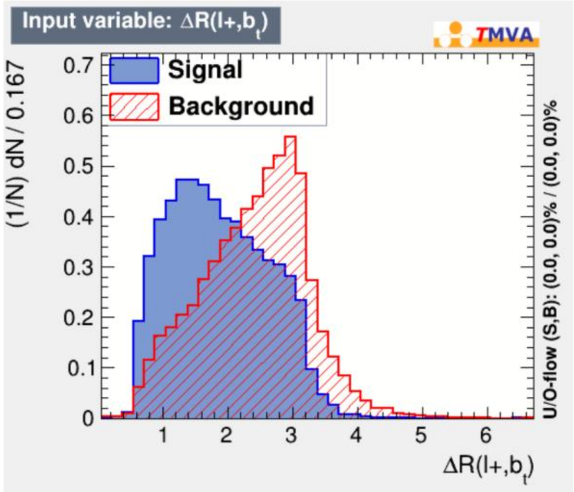
- **Most significant backgrounds**: $t\bar{t}$ +3 jets, $t\bar{t}V$ + 1 jet, $t\bar{t}H$, single top, V + 4 jets, $Vb\bar{b}$ + 2 jets, VV (V = W, Z).
- **Pythia** used for showering and hadronization. **DELPHES** used for a fast simulation of an LHC-like detector.

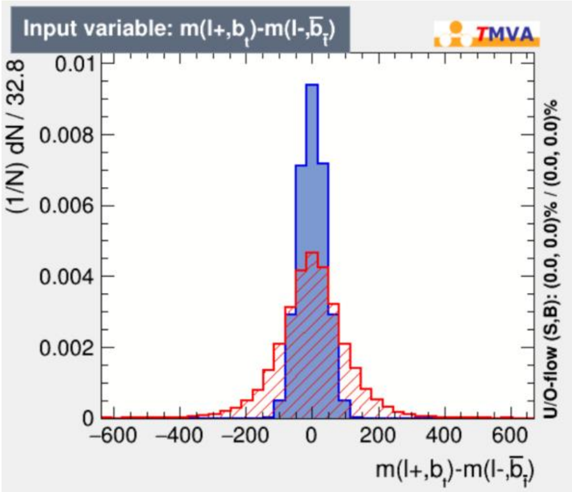
- **Selection cuts:**
  - $N_{jets} \geq 2$ and $N_{lep} \geq 2$;
  - $p_T > 20$ GeV and $|\eta| < 2.5$;
  - $|m_{l+l-} - m_Z| > 10$ GeV.

- **Boosted decision trees** (BDTs) algorithm is used to correctly assign the reconstructed jets to the b-quarks of the top-quarks.

Variables used for training and testing the BDTs:

ΔR, Δϕ, Δθ, m^{inv} of pairs (b_t, l+), ($\bar{b}_{\bar{t}}$, l-).





Event generation, selection and kinematic reconstruction

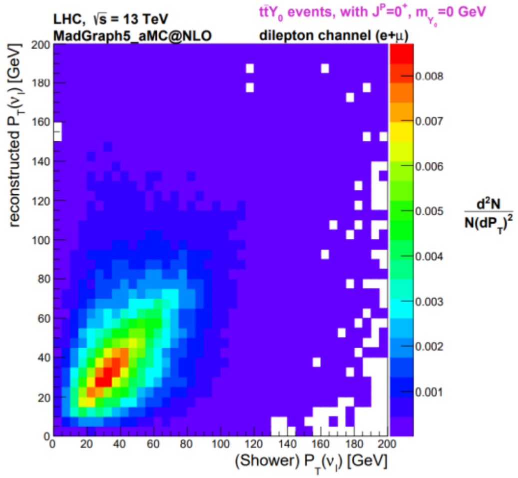
- The **3-momentum of the undetected neutrinos** are reconstructed by imposing the following energy-momentum conservation conditions. If several solutions exist, a likelihood function is built using parton level information and the solution with the highest likelihood is picked.

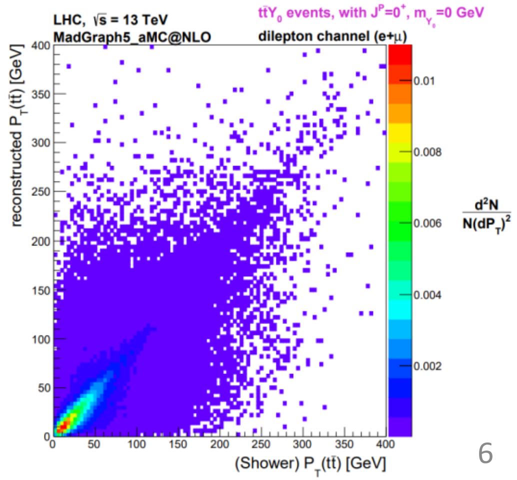
$$
\begin{aligned}
(p_\nu + p_{\ell^+})^2 &= m_W^2, \\
(p_{\bar\nu} + p_{\ell^-})^2 &= m_W^2, \\
(p_{W^+} + p_b)^2 &= m_t^2, \\
(p_{W^-} + p_{\bar b})^2 &= m_{\bar t}^2,
\end{aligned}
\qquad
\begin{aligned}
p_\nu^x + p_{\bar\nu}^x &= \not{E}^x, \\
p_\nu^y + p_{\bar\nu}^y &= \not{E}^y,
\end{aligned}
\qquad
L \propto \frac{1}{p_{T_\nu} p_{T_{\bar\nu}}} P(p_{T_\nu}) P(p_{T_{\bar\nu}}) P(p_{T_t}) P(p_{T_{\bar t}}) P(p_{T_{t\bar t}})
$$

- The **total missing transverse energy is fully accounted for by the neutrinos** (the DM mediator contribution is negligible). For a massless DM mediator, around 70% of all events were correctly reconstructed (similar efficiency is observed in typical SM $t\bar{t}$ analyses).

- **High correlation between parton level and reconstructed kinematics**

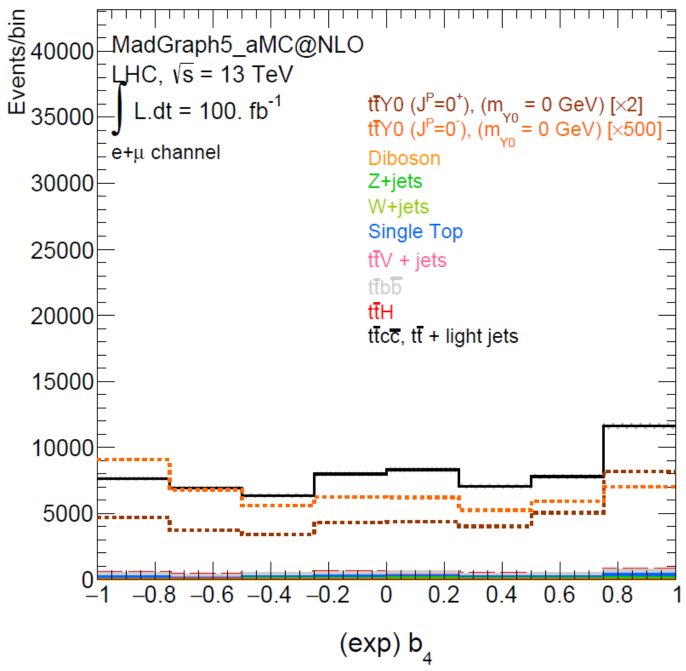
allows to study changes in angular distributions of $t\bar{t}$ systems in the presence of new invisible particles (since it is possible to reconstruct the $t\bar{t}$ system without even trying to reconstruct the invisible DM mediator).

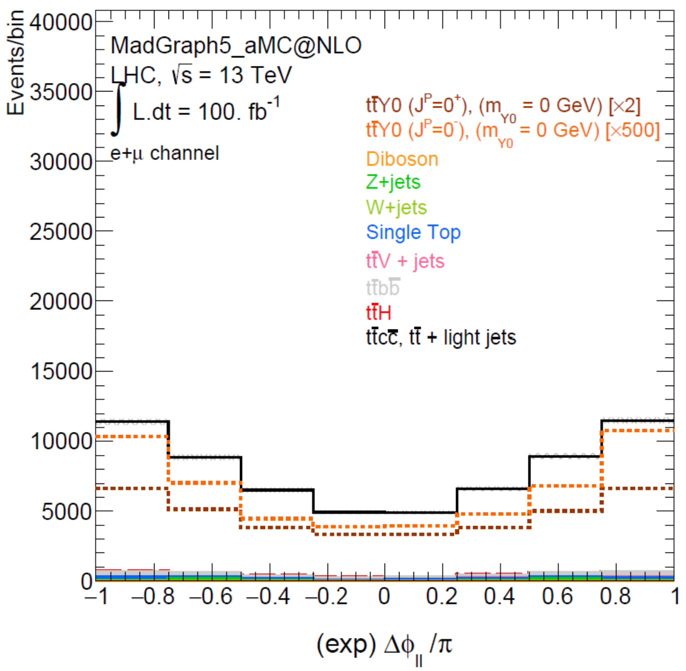


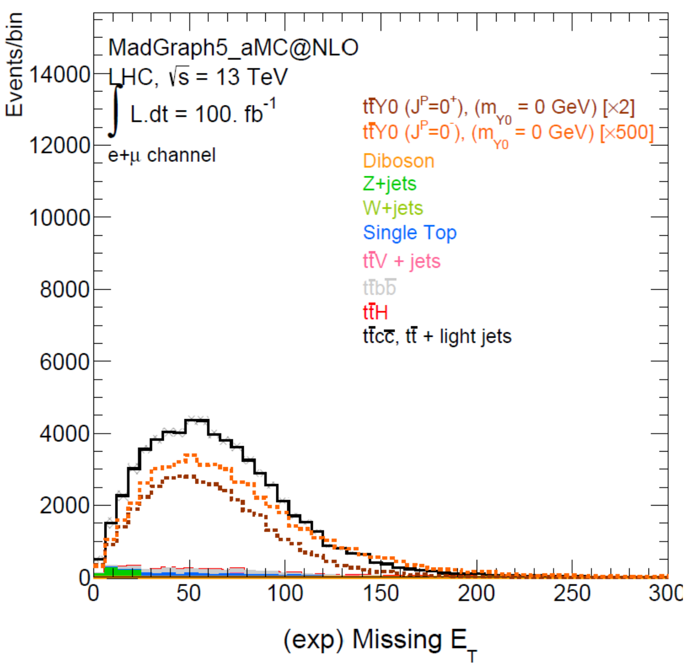


Azevedo, Capucha, Gouveia, Onofre, Santos - 2003.09043, 2012.10730, 2208.04271

Results







- The **main SM background is the $t\bar{t}$** due to its similarity with the signal final state topology. All other backgrounds are essentially residual.

- 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 DM in $t\bar{t}$ final states.

Results

- **Confidence level (CL) limits for the Yukawa couplings as a function of the mediator mass** were set, using the $\boldsymbol{\Delta\phi_{l^+l^-}}$ and $\mathbf{b_4}$ distributions.

- These exclusion limits are shown as contour plots in the (g^S_{u33}, g^P_{u33}) 2D plane, for **fixed LHC luminosities** of **200 fb^{-1}** (RUN 2 + first year of RUN 3) and **3000 fb^{-1}** (HL-LHC).

- The CLs are extracted from an ensemble of pseudo experiments using a hypothesis test. **Only statistical uncertainties** are considered. **Two scenarios:**

➢ **Scenario 1:** exclusion of the SM + CP-mixed massless DM mediator, assuming the SM as null hypothesis **(before discovery)**.
➢ **Scenario 2:** same signal hypothesis, but now null hypothesis is the SM + CP-even massless DM mediator **(upon discovery)**.

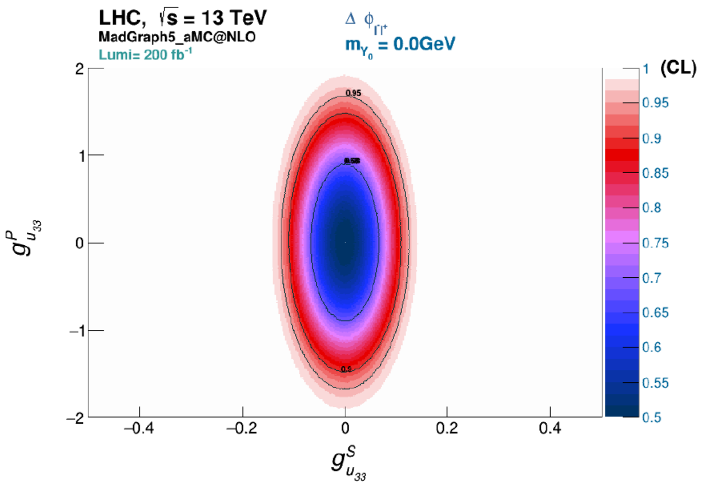
CP-mixed cross-section is given by:

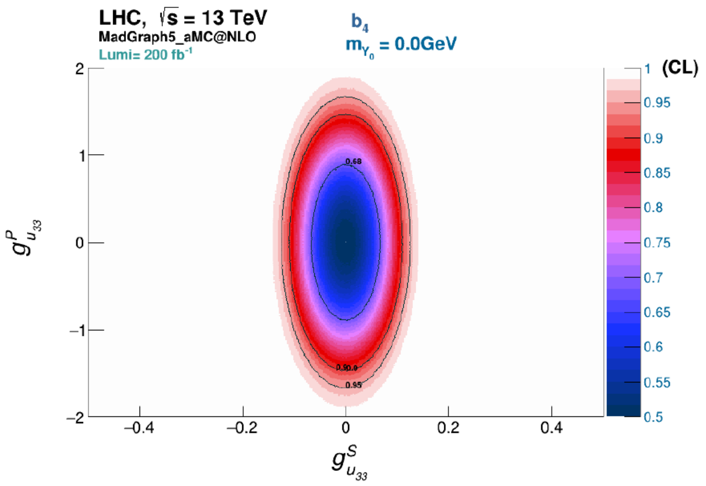
$$\boldsymbol{\sigma_{\mathrm{CP-mixed}} = (g^S_{u33})^2\, \sigma_{\mathrm{CP-even}} + (g^P_{u33})^2\, \sigma_{\mathrm{CP-odd}}}$$

Results – scenario 1

- The **exclusions limits are identical for both observables**. For L = 3000 fb^{-1}, we observe an improvement by factors of 2 to 3 on the exclusion limits.

- Similar results were obtained when using a simple counting experiment, thus the **observable choice has little to no impact on the exclusion limits in this scenario** and the DM mediator production cross section is the dominant factor.

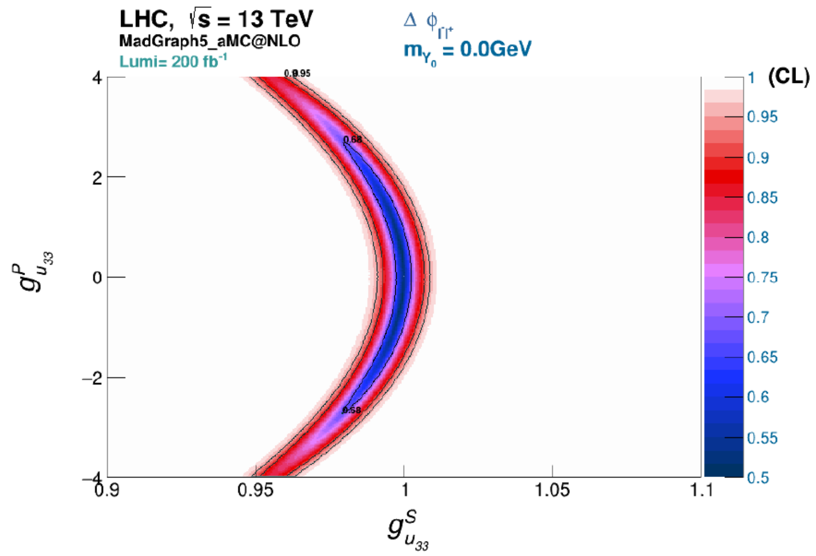


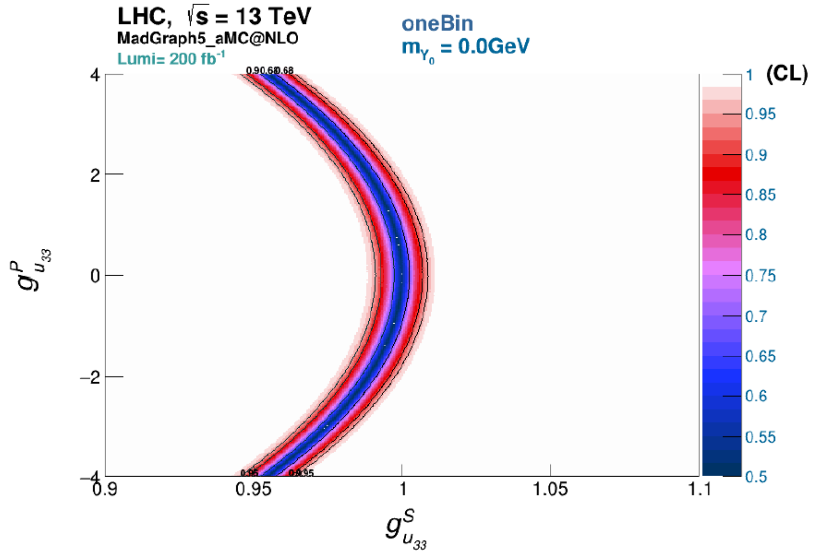


Exclusion Limits from $\Delta\phi_{l^+l^-}$		$L = 200$ fb^{-1} (68% CL)	$L = 200$ fb^{-1} (95% CL)	$L = 3000$ fb^{-1} (68% CL)	$L = 3000$ fb^{-1} (95% CL)
$m_{Y_0} = 0$ GeV	$g^S_{u33} \in$	[-0.067, +0.067]	[-0.125, +0.125]	[-0.022, +0.022]	[-0.052, +0.052]
	$g^P_{u33} \in$	[-0.91, +0.91]	[-1.71, +1.71]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

Results – scenario 2

- **Main goal** of this scenario: **study the CP-nature of the DM mediator in case of a discovery**.
- In this scenario, the difference between both distributions is quite clear, thus, **the chosen angular observable will have an important impact** on determining the CP-nature of DM mediators upon discovery.





Results – heavier masses

- Results extended to a **massive DM mediator**, with m_{Y_0}= 1, 10, 125 GeV. As expected, **exclusion limits worsen as masses increase** in both scenarios, since the $t\bar{t}Y_0$ production cross section decreases for heavier Y_0 masses.

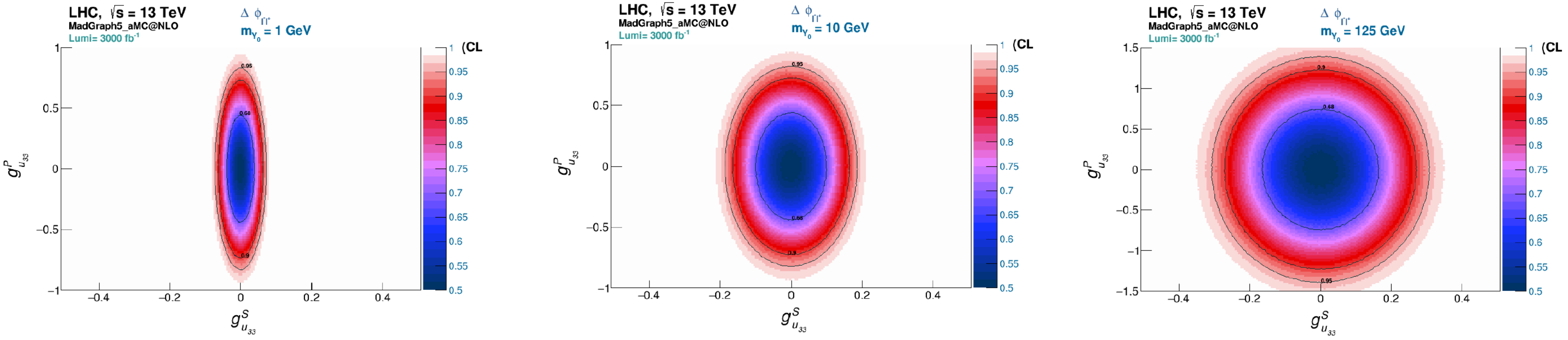
- The observable choice can have some impact on the exclusion limits, even in scenario 1, for heavier masses, because of the cross section decrease.

Scenario 1

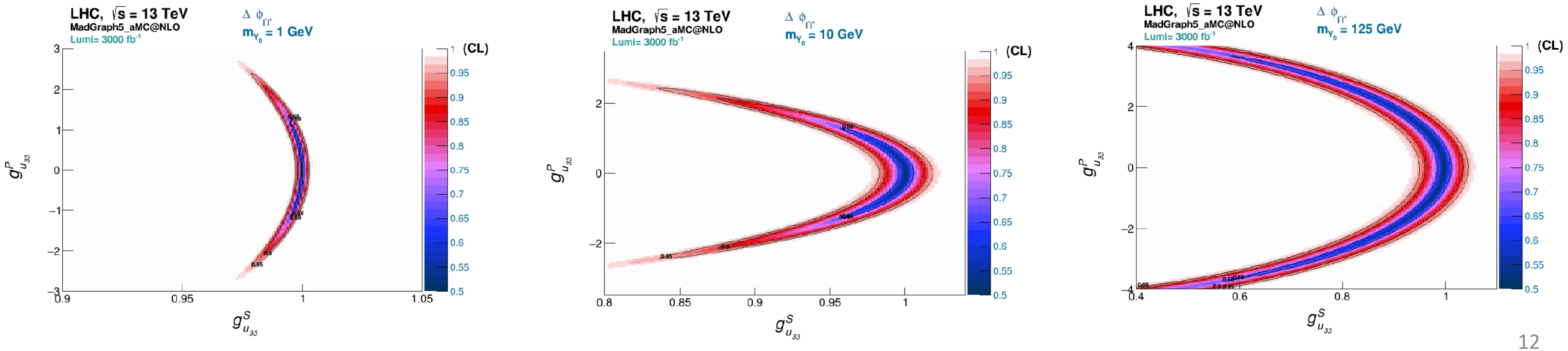
Exclusion Limits from $\Delta\phi_{l^+l^-}$		$L = 200\ \text{fb}^{-1}$ (68% CL)	$L = 200\ \text{fb}^{-1}$ (95% CL)	$L = 3000\ \text{fb}^{-1}$ (68% CL)	$L = 3000\ \text{fb}^{-1}$ (95% CL)
$m_{Y_0} = 1$ GeV	$g^S_{u33} \in$	[-0.073, +0.073]	[-0.142, +0.142]	[-0.038, +0.038]	[-0.068, +0.068]
	$g^P_{u33} \in$	[-0.89, +0.89]	[-1.65, +1.65]	[-0.43, +0.43]	[-0.83, +0.83]
$m_{Y_0} = 10$ GeV	$g^S_{u33} \in$	[-0.198, +0.198]	[-0.368, +0.372]	[-0.098, +0.098]	[-0.188, +0.188]
	$g^P_{u33} \in$	[-0.87, +0.87]	[-1.65, +1.65]	[-0.44, +0.44]	[-0.83, +0.83]
$m_{Y_0} = 125$ GeV	$g^S_{u33} \in$	[-0.328,+0.322]	[-0.608, +0.612]	[-0.162, +0.162]	[-0.308, +0.308]
	$g^P_{u33} \in$	[-1.48, +1.49]	[-2.77, +2.78]	[-0.75, +0.75]	[-1.41, +1.41]

Results – heavier masses

Scenario 1



Scenario 2



Conclusions

- **We explored the idea of using on-going $t\bar{t}$ searches to look for very light spin-0 DM mediators produced alongside a $t\bar{t}$ pair**. An approach to fully reconstruct the kinematics of the $t\bar{t}$ system present in $t\bar{t}Y_0$ events at the LHC, without attempting to reconstruct the invisible DM mediator, was presented. **Exclusion limits for the Yukawa couplings of the mediator as a function of its mass were set**, using the $\Delta\phi_{l+l-}$ and b_4 distributions, for fixed LHC luminosities of 200 fb^{-1} and 3000 fb^{-1}. Two distinct scenarios were considered.

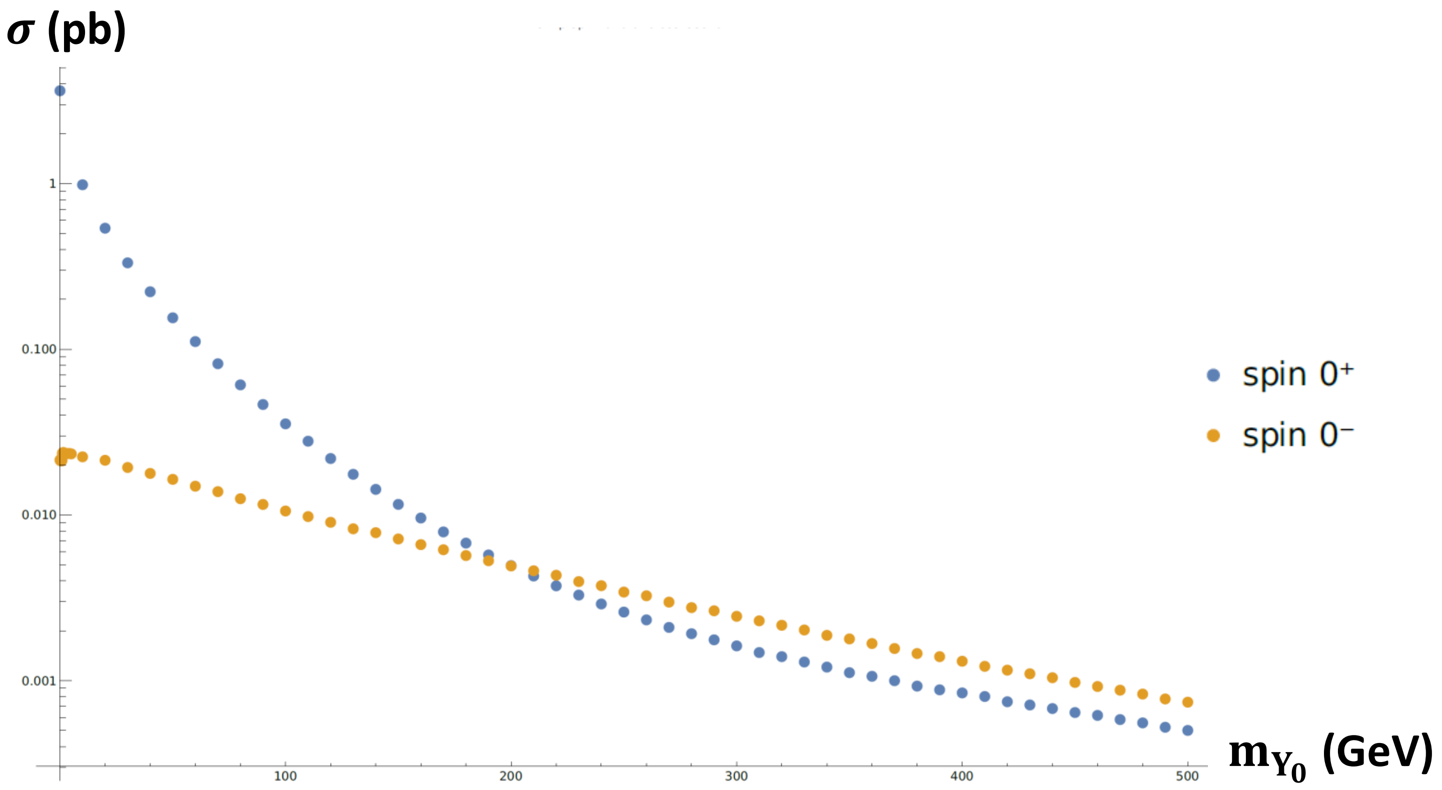
- **In scenario 1**, we observe that **the observable choice has a negligible impact on those limits**, since the DM mediator production cross section is the dominant factor (similar results were obtained with a simple counting experiment). **The 95% CL limits were $g^S_{u33} \in [-0.052, 0.052]$ and $g^P_{u33} \in [-0.85, 0.85]$, for L = 3000 fb^{-1}.**

- **In scenario 2**, where we wish to understand the CP-nature of the DM mediator upon discovery, we concluded that **the use of angular distributions can improve the exclusion limits**.

- Finally, we extended our study to the case of a **massive DM mediator**. We observed that the **exclusion limits got worse for increasing Y_0 masses**, since the $t\bar{t}Y_0$ cross section decreases in that case.

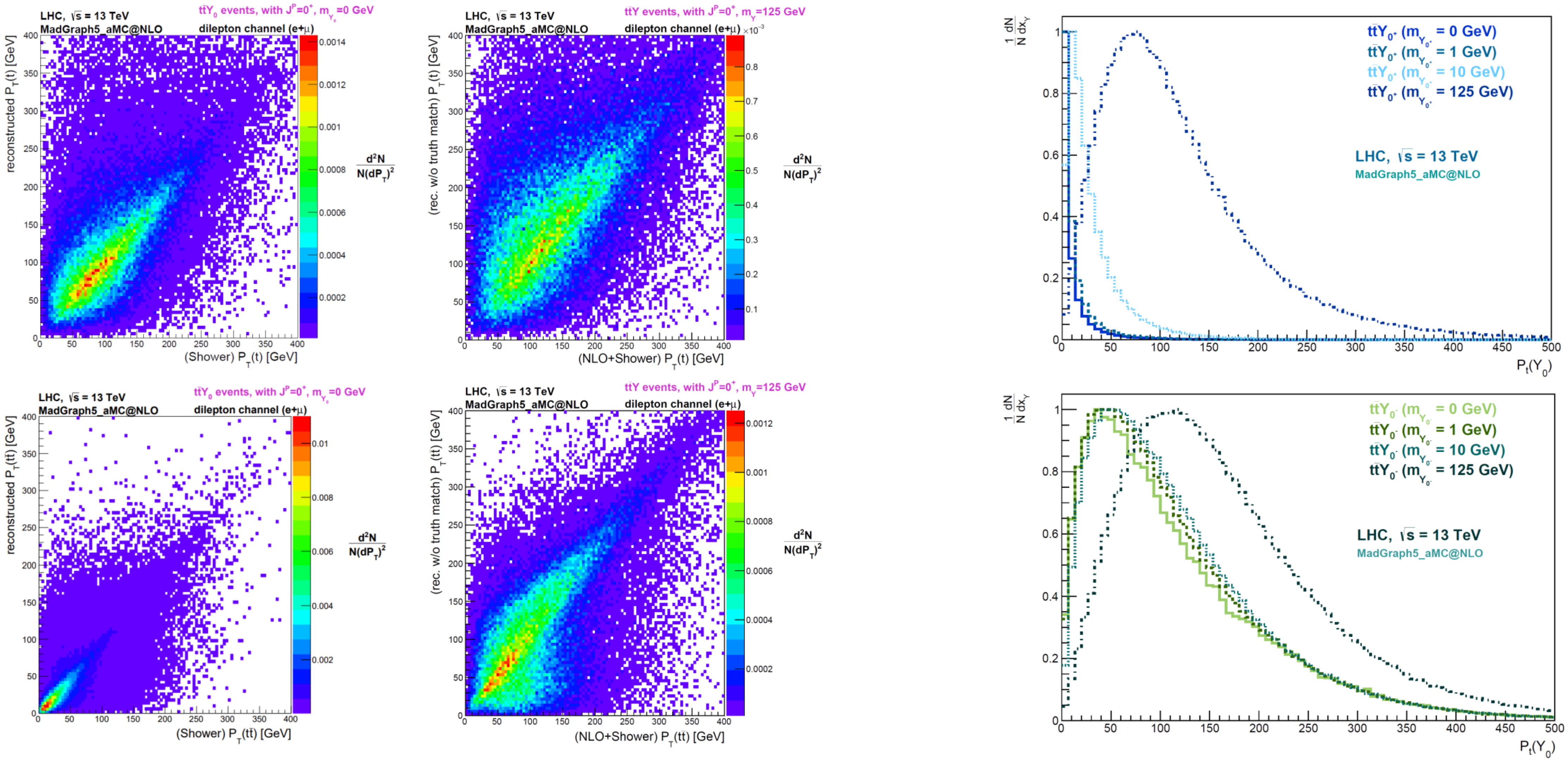
THE END.
THANK YOU!

$\sigma_{t\bar{t}Y_0}$ vs m_{Y_0}



Total $t\bar{t}Y_0$ cross section computed in MadGraph5_aMC@NLO at LO, using the DMsimp model.

Kinematic reconstruction



The reconstruction efficiency tends to get worse for heavier masses, since the contribution to the total missing transverse energy from the DM mediator increases.