Associated $t\bar{t}$ Production with Invisible Particles @ the LHC

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Fundação para a Ciência e a Tecnologia

Outline

The LHC has become a t-quark factory:

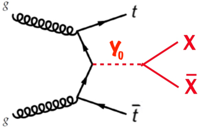
$t\bar{t}$, $t\bar{t}+X$ ($X=H,\gamma,W,Z$), single-top...

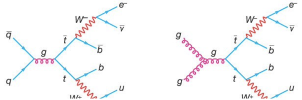
☞ window for precision SM tests

Looking into top quark precision tests

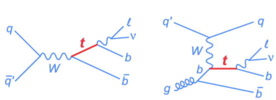
☞ can invisible particles spoil precision measurements?

- Double Top Quark Production @ LHC
- Spin Observables (mainly $t\bar{t}$ spin correlations)
- $t\bar{t}+Y_0$ production @ LHC Angular distributions and Asymmetries [JHEP 11 (2023) 125] [arXiv:2404.10852, 16 april 2024]

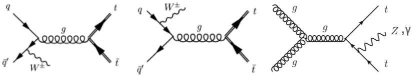




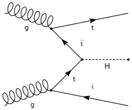
($t\bar{t}$)



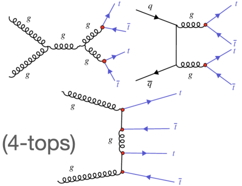
(single-t)



($t\bar{t}$+W) ($t\bar{t}$+Z,γ)



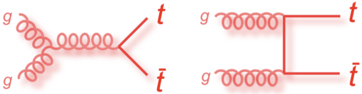
($t\bar{t}$H)

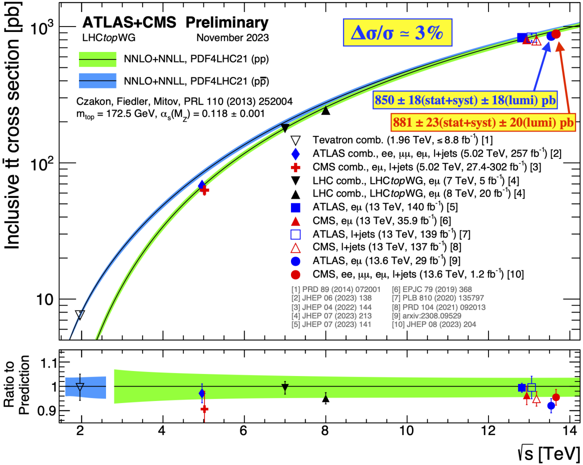


(4-tops)

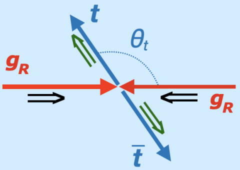
Double Top Quark Production @ LHC

- t-quark is the heaviest known fundamental fermion
  m_t = 172.52 ± 0.33 GeV (LHC comb. Nov. 2023)
  ☞ Large Yukawa coupling
- dominant decay: $t \to bW^+$
  $\mathrm{BR}(t \to sW) \leq 0.18\%$,
  $\mathrm{BR}(t \to dW) \leq 0.02\%$
- $\tau_t = \left(3.29^{+0.90}_{-0.63}\right) \times 10^{-25}\mathrm{s}$
  [PRD 85091104,2012]
  $\Rightarrow$ t-quark decays before hadronizing
  polarization transf. to decay products.
- $t\bar{t}$ production @ LHC





Produced unpolarised, *t*-quark spins are correlated



$$\sigma = \sigma_{RR} + \sigma_{LL} + \sigma_{RL} + \sigma_{LR}$$

t-quark decays

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_\ell} = \frac{1}{2}(1 + \kappa_\ell \cos\theta_\ell)$$

Normalised differential cross section

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1^i\, d\cos\theta_2^j} = \frac{1}{4}(1 + B_1^i \cos\theta_1^i + B_2^j \cos\theta_2^j - C_{ij}\cos\theta_1^i \cos\theta_2^j)$$

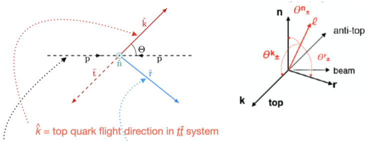
θ_1^i (θ_2^j) = ℓ^+ (ℓ^-) directions in the $t(\bar{t})$ system, with respect to $i(j)$ axis $(\hat{r},\hat{k},\hat{n})$

B_1 (B_2) = top (anti-top) vector spin polarisations C = spin correlation matrix

Spin properties completely determined by 15 coefficients that may be probed individually:

$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}(1 + [\text{Coeff.}]\,x)\, f(x)$$

Reference system
[JHEP12(2015)026]



$$\hat{\mathbf{p}}_p = (0,0,1)\,,\quad \hat{\mathbf{r}}_p = \frac{1}{r_p}(\hat{\mathbf{p}}_p - y_p\hat{\mathbf{k}})\,,\quad \hat{\mathbf{n}}_p = \frac{1}{r_p}(\hat{\mathbf{p}}_p \times \hat{\mathbf{k}})\,,$$

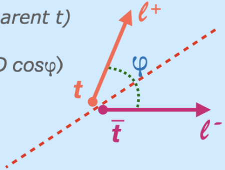
$$y_p = \hat{\mathbf{p}}_p \cdot \hat{\mathbf{k}}\,,\quad r_p = \sqrt{1 - y_p^2}\,.$$

Spin Observables @ LHC

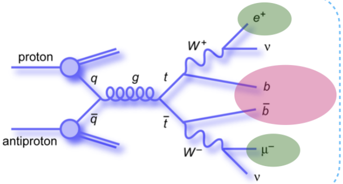
Other observables maybe used to probe Spin Correlations in $t\bar{t}$ Dileptonic Events

i) opening angle (leptons in their parent t)

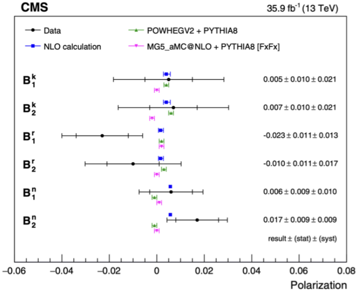
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$

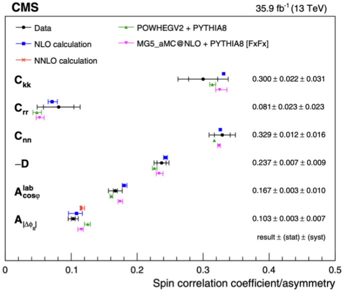


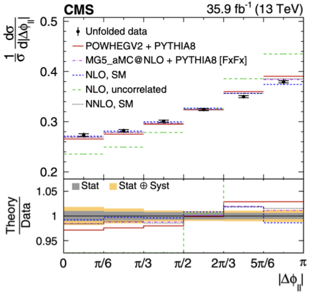
ii) $\Delta\phi_{ll}$ in LAB frame



PRD 100 (2019) 072002 (CMS)







Can invisible particles change significantly distributions? A Spin Perspective

$t\bar{t} + Y_0$ production @ LHC

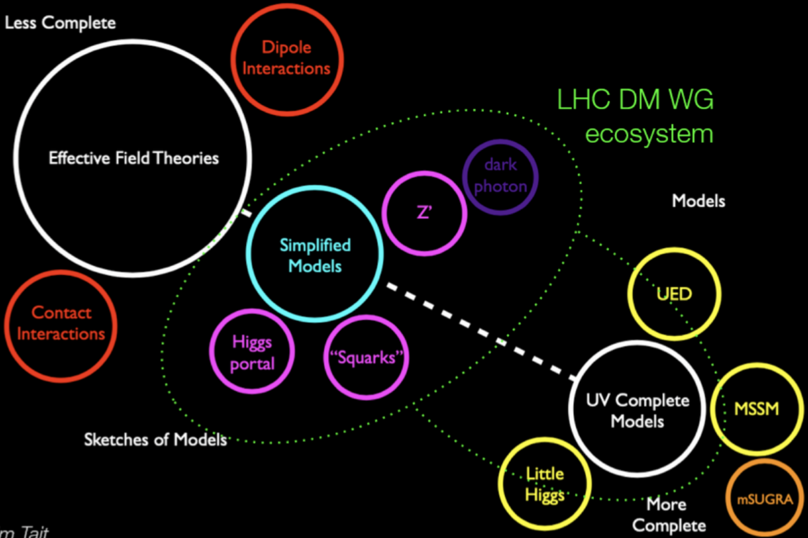


Figure: Tim Tait

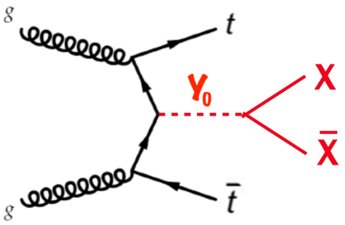
$t\bar{t} + Y_0$ production @ LHC

Interaction Lagrangians for Spin 0 [EPJC 75, 482 (2015)].

$$\mathcal{L}_{SM}^{Y_0} = \left[\bar{t}\frac{y_{33}^t}{\sqrt{2}}\left(g_{u_{33}}^S + ig_{u_{33}}^P\gamma^5\right) t\right] Y_0,$$

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

- CP-Even ($g_{u_{33}}^S = 1, g_{u_{33}}^P = 0$)
- CP-Odd ($g_{u_{33}}^S = 0, g_{u_{33}}^P = 1$)
- CP-Mixed ($g_{u_{33}}^{S/P} \neq 0$)



Dileptonic final states of the $t\bar{t}$ system is again used here:
$t\bar{t} \to W^+bW^-\bar{b} \oplus W^+(W^+) \to l^+\nu_{l^+}(l^-\bar{\nu}_{l^-})$, and $l = e, \mu$.

$t\bar{t} + Y_0$ production @ LHC

The strategy:

- Look for DM particles hidden in $t\bar{t}$ events, in particular very light particles (bellow GeV) produced with a $t\bar{t}$ pair;
  - ☞ motivated by Cosmology e.g., GW190521 re-interpretation PRL 126 (2021) 8, 081101 and PRD 108 (2023) 12, 123020
  - ☞ Sun-like star orbiting a compact object, MNRAS 524 (2023) 3, 4083
- Apply the usual $pp \rightarrow t\bar{t}$ dileptonic analysis to $pp \rightarrow t\bar{t}Y_0$;
- Y_0 is a spin-0 DM mediator that couples to both DM and SM particles;

$t\bar{t} + Y_0$ production @ LHC

Generated LHC-like signal and background events at $\sqrt{s} = 13 - 14$ TeV using `MadGraph5_aMC@NLO`
Signal events ($pp \to t\bar{t}Y_0$) generated with DMsimp [EPJC 75, 482 (2015)], for both pure scalar ($J^{CP} = 0^+$) and pseudo-scalar ($J^{CP} = 0^-$) mediators.
The mediator is, for now, not allowed to decay.

☞ The focus is the top quarks mediator interaction!!

- SM dominant Backgrounds: $t\bar{t}$, $t\bar{t}H$, $t\bar{t}V(V = Z, W^{\pm})$ and single-t.
- Delphes used for a fast simulation of an LHC detector.

Selection Cuts

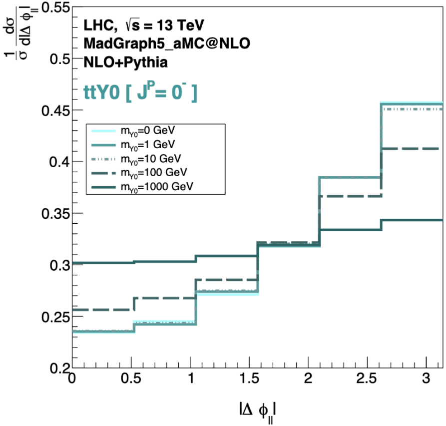
Events must have at least 2 opposite sign leptons and 2 b-jets with $p_T \geq 20$ GeV and $|\eta| \leq 2.5$ (remove back. $|m_Z$-91GeV$|$>10 GeV).

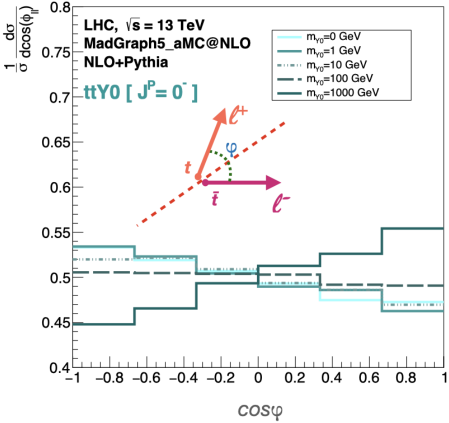
DM Effects in $t\bar{t}$ Spin Observables

$t\bar{t}$ entanglement will be affected

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$

Leptons azimuthal angle difference (LAB)





$t\bar{t} + Y_0$ production @ LHC

Kinematic Reconstruction

The undetected neutrinos are reconstructed by imposing $(E, \vec{p})$ conservation

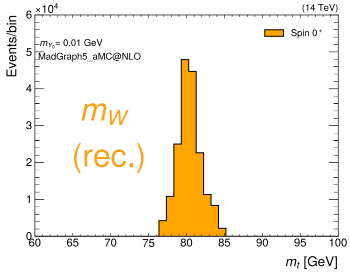
$$(P_{W^+} + P_b)^2 = m_t^2$$

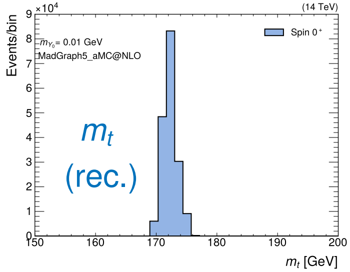
$$(P_{W^-} + P_{\bar{b}})^2 = m_t^2 \qquad p_\nu^x + p_{\bar{\nu}}^x = \not{E}_T^x$$

$$(P_\nu + P_{l^+})^2 = m_{W^+}^2 \qquad p_\nu^y + p_{\bar{\nu}}^y = \not{E}_T^y$$

$$(P_{\bar{\nu}} + P_{l^-})^2 = m_{W^-}^2$$

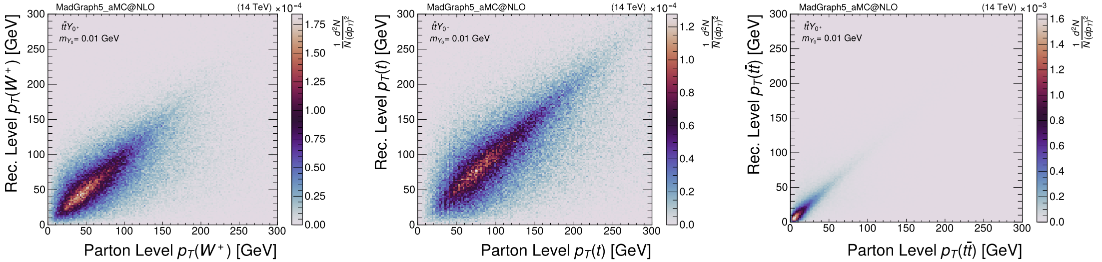
- ☞ $\not{E}_T$ fully accounted for by the neutrinos
- ☞ DM mediator contribution is considered negligible (approximation)





$t\bar{t} + Y_0$ production @ LHC

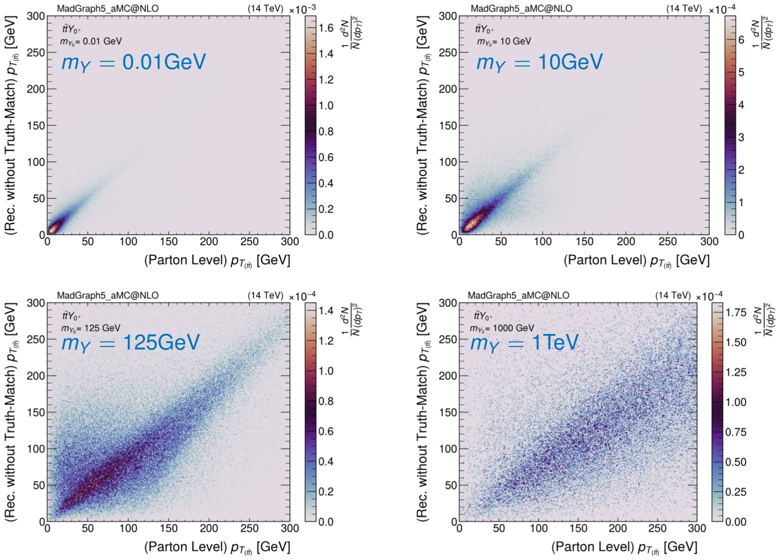
☞Strong correlation between Parton Level and Reconstructed Kinematics.



What does this tell us?

- Reconstructed kinematics enables studying angular distributions of $t\bar{t}$ systems in the presence of new invisible particles!
- Possible to reconstruct the $t\bar{t}$ system of $t\bar{t}Y_0$ events without even trying to reconstruct the invisible DM mediator (Y_0)

$t\bar{t} + Y_0$ production @ LHC



The approximation progressively looses validity as the mediator mass increases.

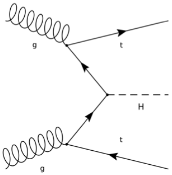
Since we cant get rid of these events, can we probe DM @ the LHC with t-quark angular distributions?....

Spin CP-sensitive observables have been quite powerful in ttH!

$t\bar{t} + H$ production @ LHC

Effective Lagrangian for $t\bar{t}H$ interaction

[PRD**100**,075034 (2019)]

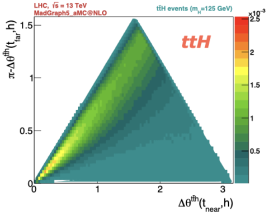


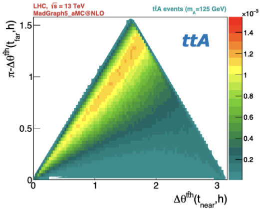
$$\mathcal{L}(Htt) = -\frac{m_t}{v}\bar{\psi}_t\,(\kappa + \mathrm{i}\,\tilde{\kappa}\gamma_5)\,\psi_t\,H,$$

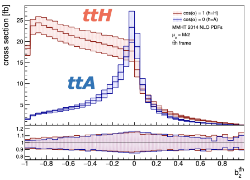
$k(\tilde{k})$ = CP-even (CP-odd) components

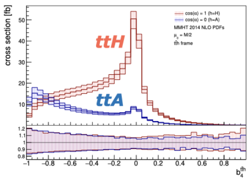
SM (pure CP-even): $k=1$ and $\tilde{k} = 0$

BSM (pure CP-odd): $k=0$ and $\tilde{k} = 1$









$$b_2^f(i,j) = \frac{(\vec{p}_i^{\,f}\times\hat{k}_z).(\vec{p}_j^{\,f}\times\hat{k}_z)}{|\vec{p}_i^{\,f}||\vec{p}_j^{\,f}|}$$

$$b_4^f(i,j) = \frac{p_{i,z}^f\;p_{j,z}^f}{|\vec{p}_i^{\,f}||\vec{p}_j^{\,f}|}$$

$$b_2 \;\propto\; \sin\theta_t \times \sin\theta_{\bar{t}}$$

$$b_4 \;\propto\; \cos\theta_t \times \cos\theta_{\bar{t}}.$$

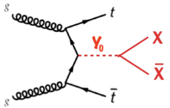
Using only $t\bar{t}$ information

Spin-parity sensitivity is clear !

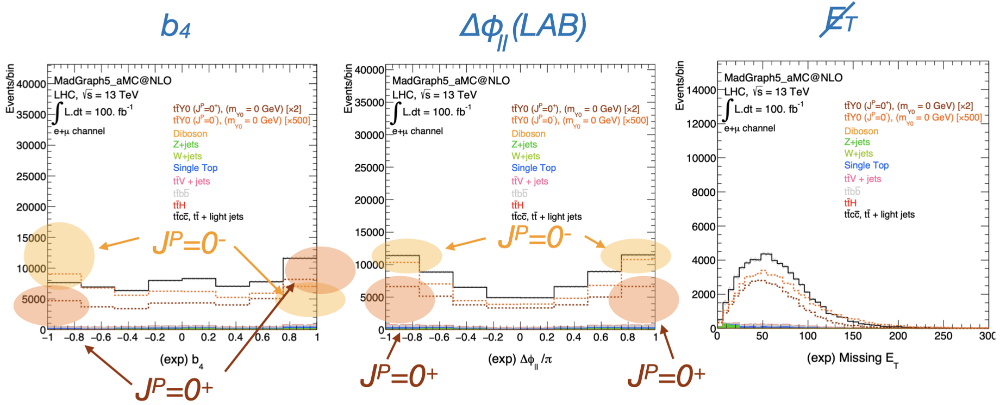
$t\bar{t} + Y_0$ production @ LHC

DM Effects in $t\bar{t}$ Spin Observables

[*JHEP* 11 (2023) 125]



only visible (rec.) particles used here
no attempt to use any information from Y_0



$t\bar{t} + Y_0$ production @ LHC

☞ Confidence level (CL) limits for the DM mediator couplings are set for several observables ($\Delta\phi_{ll}$, b_4, b_2,$\tilde{b}_2^y$,$\tilde{b}_2^d$,...).

Two different exclusion scenarios are considered:

- **Scenario 1** exclusion of the SM + new CP-Mixed DM mediator (H_1), assuming the SM as null hypothesis (H_0);

CP-Mixed cross-section is given by:

$$\sigma_{CP-Mixed} = (g^S_{u_{33}})^2 \sigma_{CP-Even} + (g^P_{u_{33}})^2 \sigma_{CP-Odd} \tag{1}$$

- **Scenario 2** exclusion of the SM + new CP-Mixed DM mediator (H_1), assuming the SM + pure CP-Even mediator, as null hypothesis (H_0) ☞ the idea is: if indeed we discover something, would we be able to test its properties?

DM Effects in $t\bar{t}$ Spin Observables

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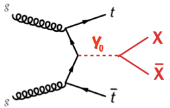
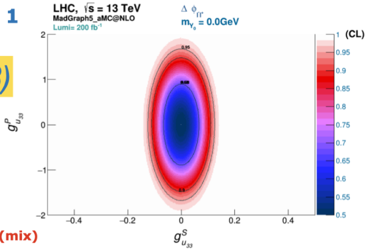
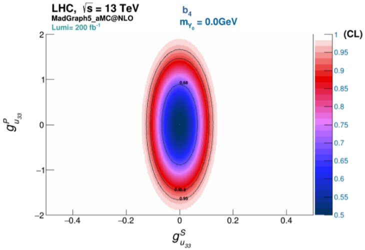


only visible (rec.) particles used here
no attempt to use any information from Y_0

Scenario 1

$\Delta\phi_{ll}$ (LAB)





b_4

H_0 = SM

H_1 = SM + $Y_{0(mix)}$

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]

$t\bar{t} + Y_0$ production @ LHC

DM Effects in $t\bar{t}$ Spin Observables

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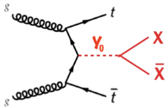
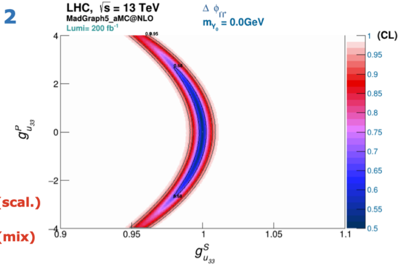


only visible (rec.) particles used here
no attempt to use any information from Y_0

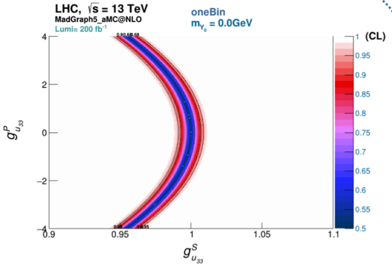
Scenario 2

H_0 = SM + $Y_{0(scal.)}$

H_1 = SM + $Y_{0(mix)}$



$\Delta\phi_{ll}$ (LAB)



cross-section measurement

spin observables seem to have enhanced sensitivity

DM Effects in $t\bar{t}$ Spin Observables

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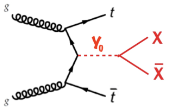


only visible (rec.) particles used here
no attempt to use any information from Y_0

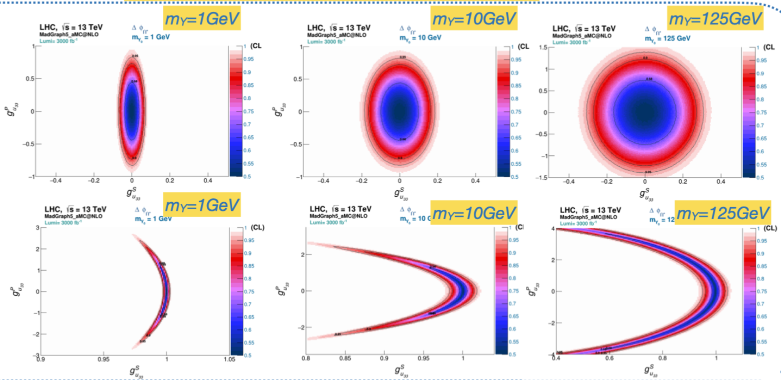
High-Luminosity LHC (3000fb^{-1})

Scenario 1

H_0 = SM
H_1 = SM + $Y_{0(mix)}$

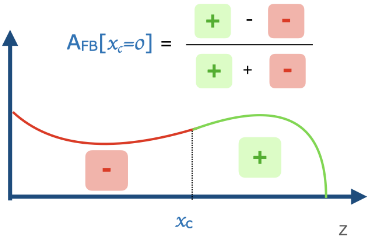
Scenario 2

H_0 = SM + $Y_{0(scal.)}$
H_1 = SM + $Y_{0(mix)}$



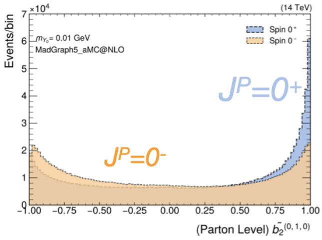
FB Asymmetries from angular distributions

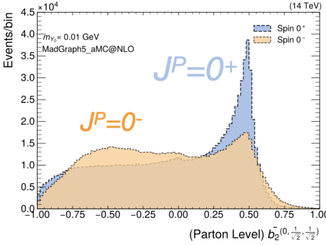
[arXiv:2404.10852]



Choice of $x_c=0$:

As usual, several axis options are available (maximize differences)



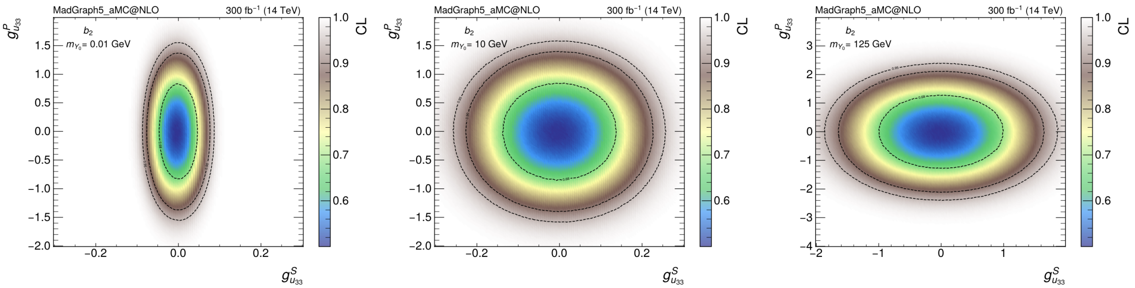


FB Asymmetries evaluated at Parton-Level:

Observable	10^{-2}GeV $t\bar{t}Y^+/t\bar{t}Y^-$	1 GeV $t\bar{t}Y^+/t\bar{t}Y^-$	10 GeV $t\bar{t}Y^+/t\bar{t}Y^-$	100 GeV $t\bar{t}Y^+/t\bar{t}Y^-$	125 GeV $t\bar{t}Y^+/t\bar{t}Y^-$
b_2	-0.839/-0.579	-0.834/-0.579	-0.819/-0.568	-0.703/-0.409	-0.674/-0.377
$\tilde{b}_2^{\hat{y}}$	+0.222/-0.042	+0.219/-0.041	+0.217/-0.049	+0.211/-0.156	+0.199/-0.180
$\tilde{b}_2^{\hat{d}}$	+0.098/-0.110	+0.092/-0.109	+0.086/-0.116	+0.061/-0.185	+0.046/-0.199

Scenario 1

CL limits for b_2 $m_{Y_0} = 0.01$GeV (**left**), $m_{Y_0} = 10$GeV (**center**), and $m_{Y_0} = 125$GeV (**right**), L =300 fb^{-1}.

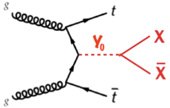


- quite consistent exclusion limits when compared with full angular distributions;

Forward-Backward Asymmetries [$x_c = 0$]

DM Effects in $t\bar{t}$ Spin Observables

[arXiv:2404.10852]



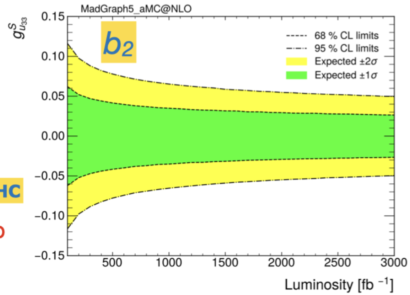
only visible (rec.) particles used here
no attempt to use any information from Y_0

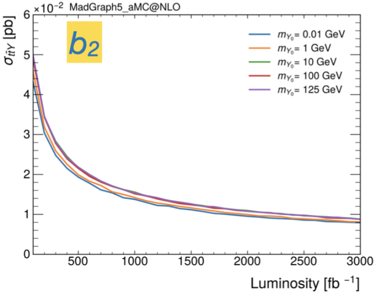
Pure Scalar DM mediator hypothesis

H_0 = SM
H_1 = SM + $Y_{0(scalar)}$

High-Luminosity LHC

σ(68%CL) ~ 10^{-2} pb





Conclusion

- The kinematic reconstruction of the $t\bar{t}$ system holds in $t\bar{t}Y_0$ events,
  ☞ if NP events is out there in the top quark sector, we cant get rid of it easily!
- Top quark spin observables are quite powerful to probe NP, when performing precision tests of the SM;
- Asymmetries can be effectively used in searches for DM.

Backup

Scenario 1 - Other Mediator Masses Explored

Exclusion Limits from b_2

m_{Y_0}		300 fb^{-1} (68% CL)	300 fb^{-1} (95% CL)	3000 fb^{-1} (68% CL)	3000 fb^{-1} (95% CL)
0.01 GeV	$g^S_{u_{33}} \in$	$[-0.0425, 0.0475]$	$[-0.0875, 0.0875]$	$[-0.0225, 0.0225]$	$[-0.0475, 0.0475]$
	$g^P_{u_{33}} \in$	$[-0.83, 0.83]$	$[-1.57, 1.57]$	$[-0.4725, 0.4575]$	$[-0.8775, 0.8925]$
10 GeV	$g^S_{u_{33}} \in$	$[-0.1375, 0.1375]$	$[-0.2575, 0.2625]$	$[-0.0775, 0.0775]$	$[-0.1425, 0.1475]$
	$g^P_{u_{33}} \in$	$[-0.85, 0.85]$	$[-1.61, 1.61]$	$[-0.4725, 0.4725]$	$[-0.8925, 0.8925]$
125 GeV	$g^S_{u_{33}} \in$	$[-1.01, 1.015]$	$[-1.885, 1.89]$	$[-0.5625, 0.5625]$	$[-1.0575, 1.0575]$
	$g^P_{u_{33}} \in$	$[-1.29, 1.27]$	$[-2.41, 2.43]$	$[-0.725, 0.725]$	$[-1.35, 1.375]$

Exclusion Limits from $\tilde{b}_2^{(0,1,0)}$

m_{Y_0}		300 fb^{-1} (68% CL)	300 fb^{-1} (95% CL)	3000 fb^{-1} (68% CL)	3000 fb^{-1} (95% CL)
0.01 GeV	$g^S_{u_{33}} \in$	$[-0.0425, 0.0425]$	$[-0.0875, 0.0875]$	$[-0.0225, 0.0225]$	$[-0.0475, 0.0475]$
	$g^P_{u_{33}} \in$	$[-0.87, 0.87]$	$[-1.65, 1.67]$	$[-0.4875, 0.4875]$	$[-0.9375, 0.9225]$
10 GeV	$g^S_{u_{33}} \in$	$[-0.1375, 0.1375]$	$[-0.2575, 0.2625]$	$[-0.0775, 0.0775]$	$[-0.1475, 0.1475]$
	$g^P_{u_{33}} \in$	$[-0.89, 0.91]$	$[-1.71, 1.69]$	$[-0.5025, 0.5025]$	$[-0.9525, 0.9525]$
125 GeV	$g^S_{u_{33}} \in$	$[-1.06, 1.065]$	$[-1.985, 1.99]$	$[-0.5925, 0.5925]$	$[-1.1175, 1.1175]$
	$g^P_{u_{33}} \in$	$[-1.57, 1.55]$	$[-2.93, 2.91]$	$[-0.875, 0.875]$	$[-1.65, 1.65]$

Exclusion Limits from $\tilde{b}_2^{(0,1/\sqrt{2},1/\sqrt{2})}$

m_{Y_0}		300 fb^{-1} (68% CL)	300 fb^{-1} (95% CL)	3000 fb^{-1} (68% CL)	3000 fb^{-1} (95% CL)
0.01 GeV	$g^S_{u_{33}} \in$	$[-0.0422, 0.0474]$	$[-0.0876, 0.0876]$	$[-0.0225, 0.0225]$	$[-0.0475, 0.0475]$
	$g^P_{u_{33}} \in$	$[-0.87, 0.87]$	$[-1.67, 1.67]$	$[-0.4875, 0.4875]$	$[-0.9375, 0.9375]$
10 GeV	$g^S_{u_{33}} \in$	$[-0.138, 0.138]$	$[-0.263, 0.263]$	$[-0.078, 0.078]$	$[-0.148, 0.148]$
	$g^P_{u_{33}} \in$	$[-0.92, 0.92]$	$[-1.71, 1.71]$	$[-0.5025, 0.5025]$	$[-0.9525, 0.9525]$
125 GeV	$g^S_{u_{33}} \in$	$[-1.06, 1.065]$	$[-1.985, 1.99]$	$[-0.5925, 0.5925]$	$[-1.1175, 1.1175]$
	$g^P_{u_{33}} \in$	$[-1.57, 1.55]$	$[-2.93, 2.95]$	$[-0.875, 0.875]$	$[-1.65, 1.65]$

- The exclusion limits worsen as masses increase, once the $t\bar{t}Y_0$ production cross-section decreases for heavier mediator masses;
- A considerable portion of the parameter space can already be excluded for $L = 300\ fb^{-1}$.
- Exclusion limits improve by roughly a factor of 2 when $L = 3000\ fb^{-1}$.