

Dark Matter Search in the processes of top quark production

- Theory models and current experimental limits
- Associated top quark production with dark matter
- Dark matter mediator in the production of top quarks

E. Abasov, E. Boos, V. Bunichev, P. Volkov, G. Vorochnikov, L. Dudko, A. Zaborenko, E. Iudin,
M. Perfilov, A. Markina, N. Savkova
SINP, Lomonosov Moscow State University

This study was conducted within the scientific program of the National Center for Physics and Mathematics, section #5 «Particle Physics and Cosmology»

Theory models

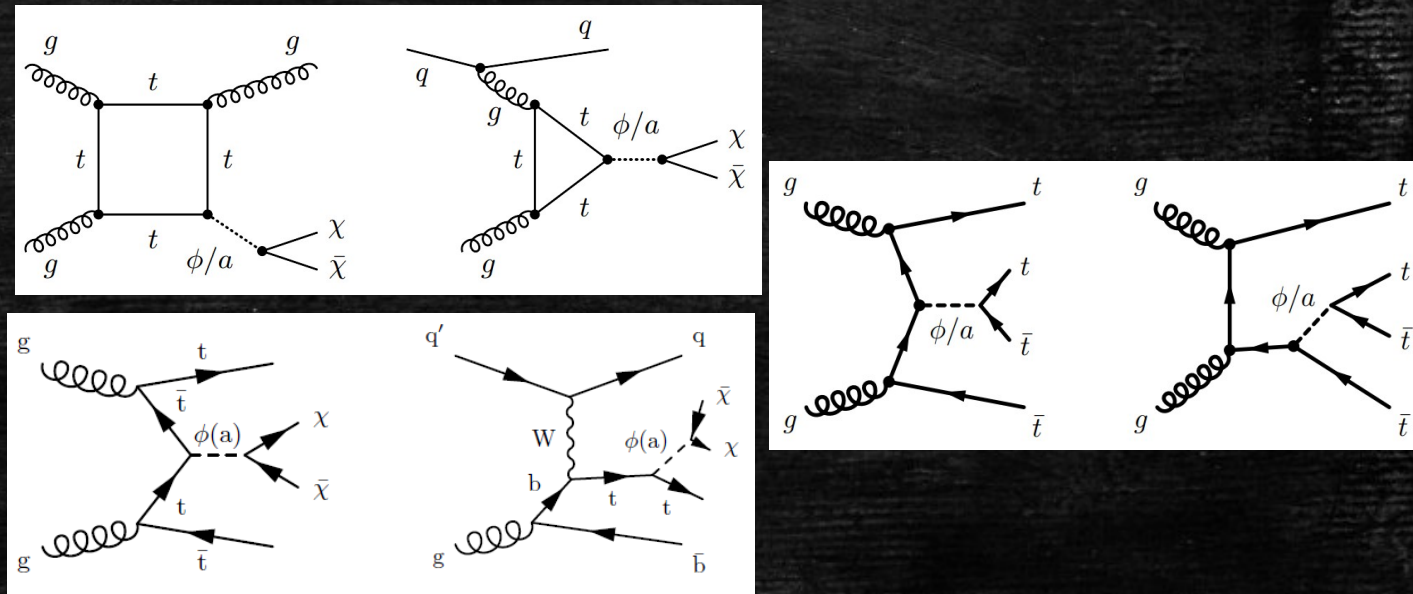
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- Simplified models is all we need to model top quark interactions with DM sector, for a while
- Search in:
 - Associated production of top quark and DM;
 - Top quark pair is produced in the decay of DM mediator
- Mostly does not depend on DM mass ($2m_\chi < m_\phi$), quadratically depends on coupling constants (equal 1 in the models, LHC-DM-WG recommendation). The main parameter is the DM mediator mass (m_ϕ)

$$L_\Phi = g_\chi \Phi \bar{\chi} \chi + \frac{g_v \Phi}{\sqrt{2}} \sum_f (y_f \bar{f} f)$$

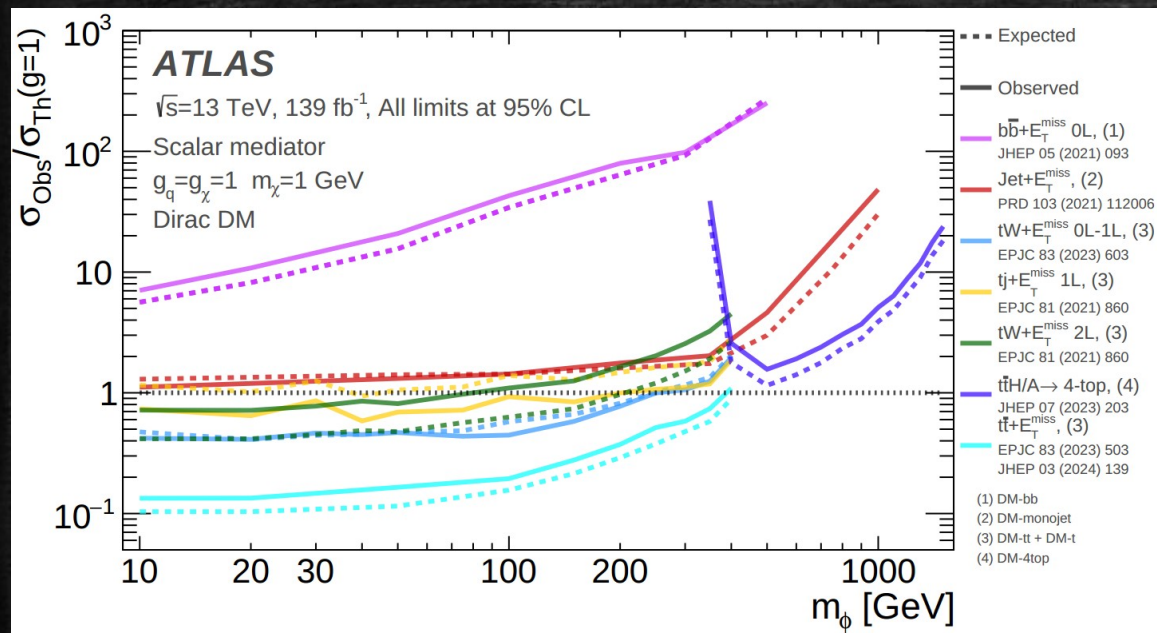
$$L_A = i g_\chi A \bar{\chi} \gamma^5 \chi + i \frac{g_v A}{\sqrt{2}} \sum_f (y_f \bar{f} \gamma^5 f)$$

$$\mathcal{L}_{\text{fermion},V} \supset V_\mu \bar{\chi} \gamma^\mu (g_\chi^V - g_\chi^A \gamma^5) \chi + \sum_{f=q,\ell,\nu} V_\mu \bar{f} \gamma^\mu (g_f^V - g_f^A \gamma^5) f$$

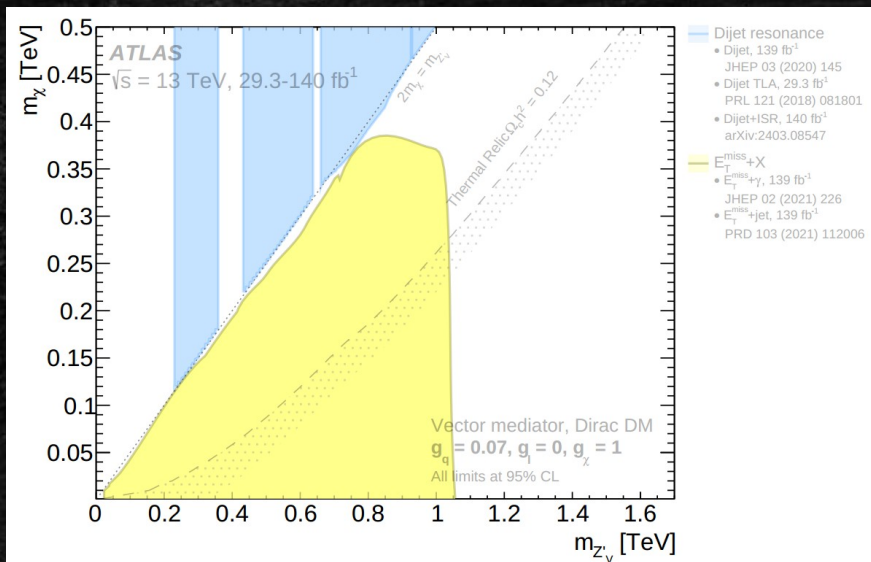
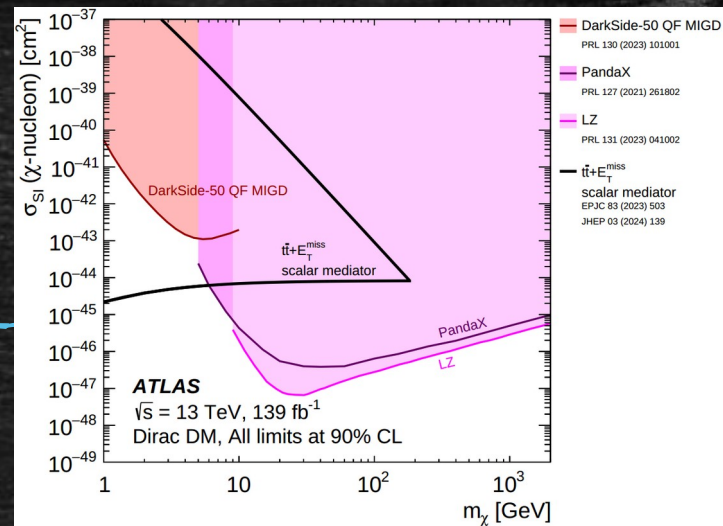


$$\{m_\chi, m_{\phi/a}, g_\chi, g_u, g_d, g_\ell\}$$

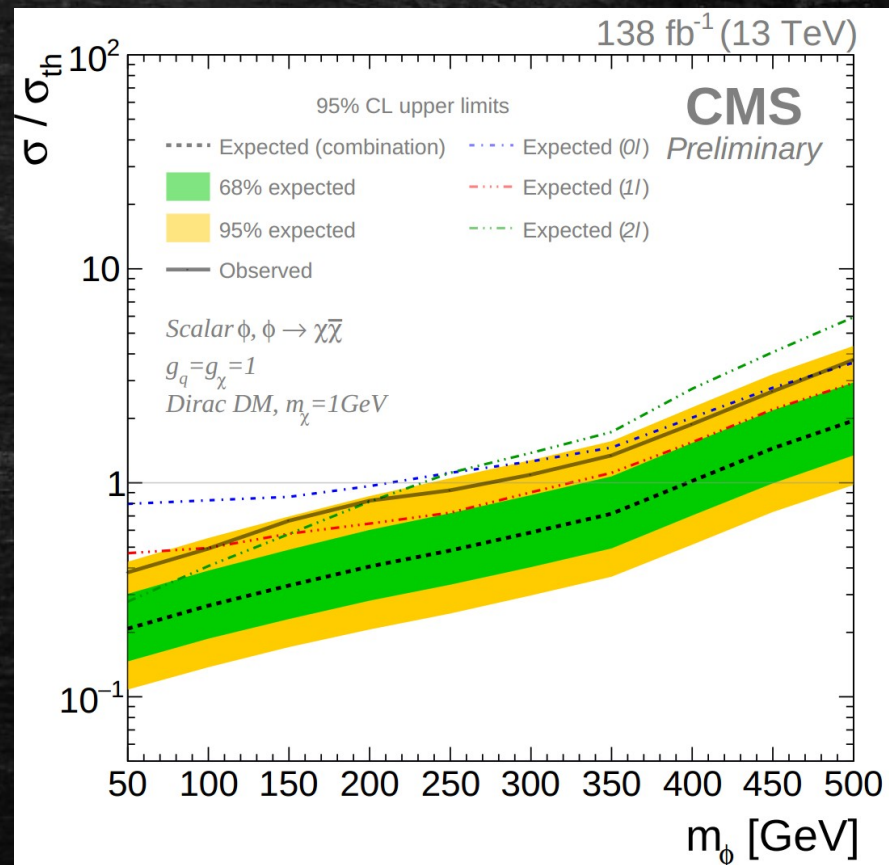
Experimental limits



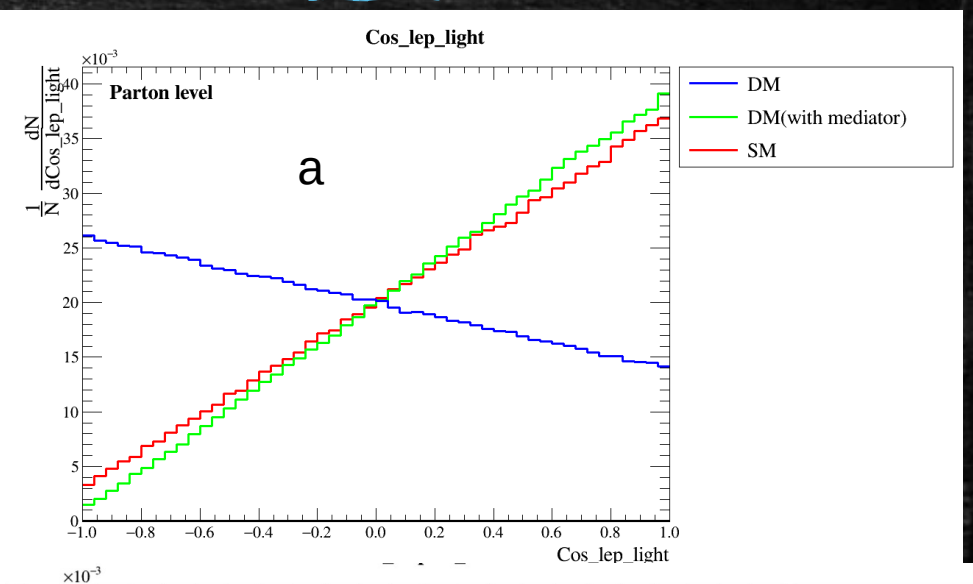
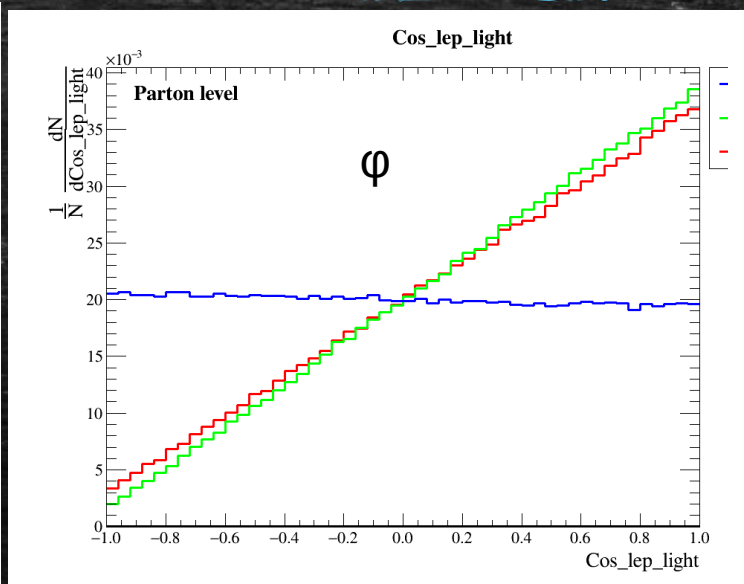
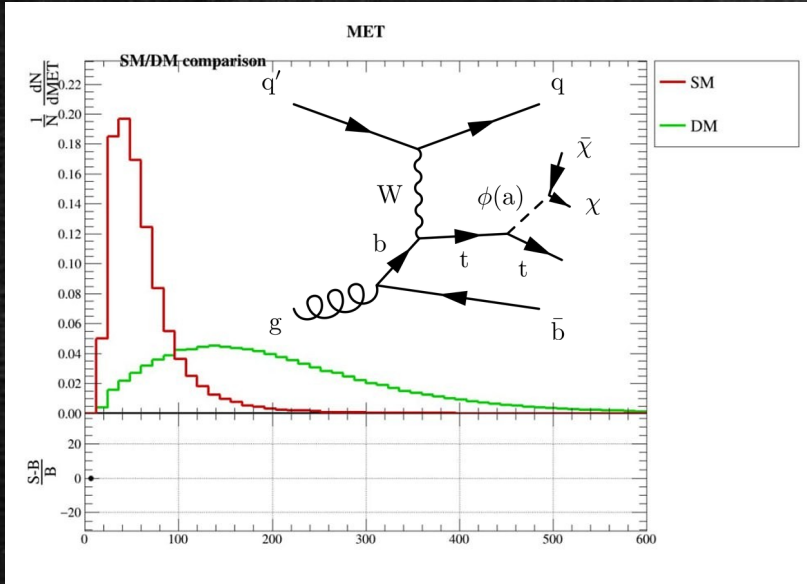
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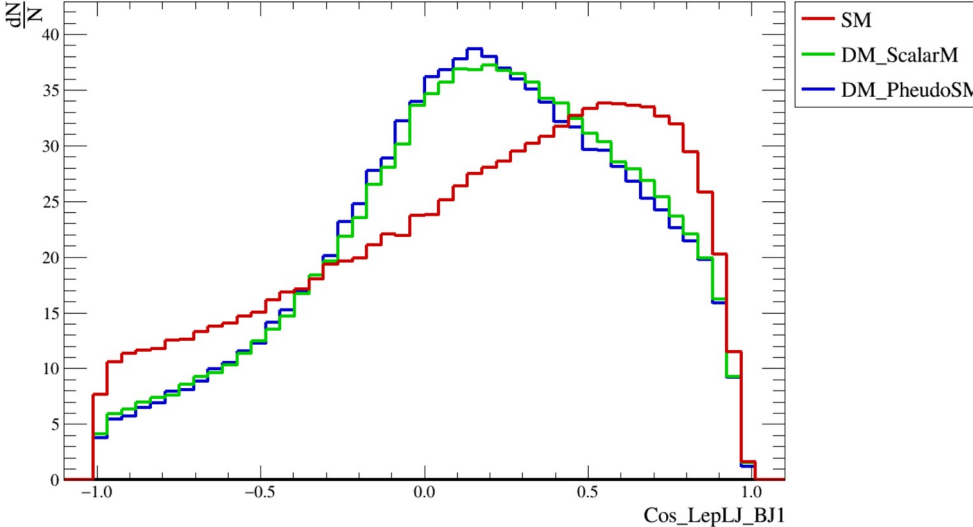
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Search methodology and observables.



New observable has proposed based on well know SM spin correlations in production and decay of top quark.
 Need to separate neutrino (from top decay) and mediator contributions to the total missing transverse energy.



Attempt to distinguish analytically neutrino and mediator momentum

$$(P_l + P_\nu)^2 = M_w^2$$

$$(P_l + P_\nu + P_b)^2 = M_t^2$$

$$MET_x = p_{\nu_x} + p_{\phi_x}$$

$$MET_y = p_{\nu_y} + p_{\phi_y}$$

$$P_\phi^2 = M_\phi^2$$

$$\left(\frac{E_\phi}{M_\phi}\right)^2 - \left(\frac{MET_x - p_{\nu_x}}{M_\phi}\right)^2 - \left(\frac{MET_y - p_{\nu_y}}{M_\phi}\right)^2 - 1 = 0$$

$$p_{\nu_x} = \pm \sqrt{dp_{\nu_y}^2 + ep_{\nu_y} + f} - \frac{\tilde{C}_x}{\tilde{C}_{x^2}} - \frac{\tilde{C}_{xy}}{\tilde{C}_{x^2}} p_{\nu_y}$$

$$d = \frac{\tilde{C}_{xy}^2 - \tilde{C}_{x^2}\tilde{C}_{y^2}}{\tilde{C}_{x^2}^2}, e = \frac{2\tilde{C}_{xy}\tilde{C}_x - 2\tilde{C}_{x^2}\tilde{C}_y}{\tilde{C}_{x^2}^2}, f = \frac{\tilde{C}_x^2 - \tilde{C}\tilde{C}_{x^2}}{\tilde{C}_{x^2}^2}$$

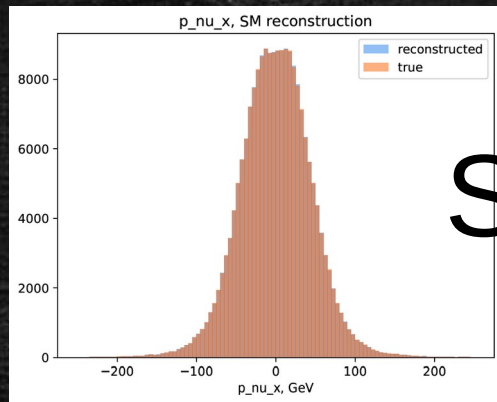
$$\tilde{C} = C^2 - \left(\frac{\tilde{A}}{p_{1b_z}}\right)^2, \tilde{C}_{x^2} = C_x^2 - \left(1 + \left(\frac{p_{1b_x}}{p_{1b_z}}\right)^2\right), \tilde{C}_{y^2} = C_y^2 - \left(1 + \left(\frac{p_{1b_y}}{p_{1b_z}}\right)^2\right),$$

$$\tilde{C}_{xy} = C_x C_y - \frac{p_{1b_x} p_{1b_y}}{p_{1b_z}^2}, \tilde{C}_x = C C_x - \frac{\tilde{A} p_{1b_x}}{p_{1b_z}^2}, \tilde{C}_y = C C_y - \frac{\tilde{A} p_{1b_y}}{p_{1b_z}^2}$$

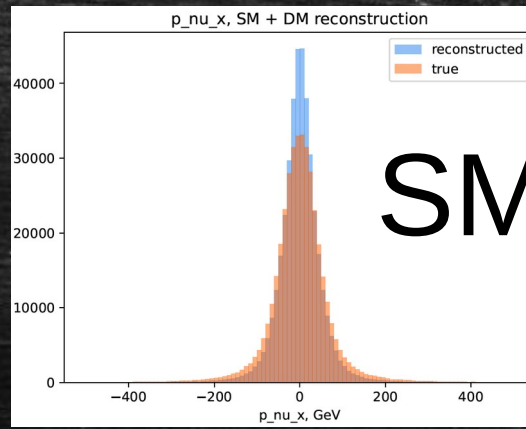
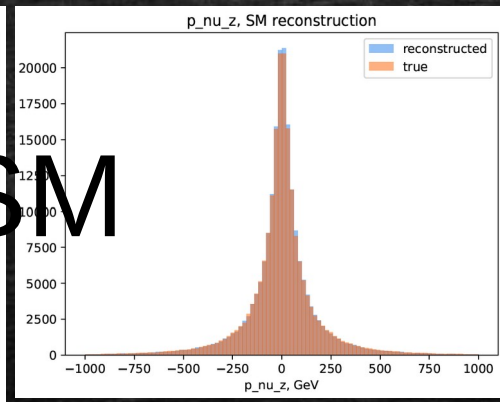
There are no strict analytical restrictions and additional approximations are required, or additional methods.

$$C = \frac{M_w^2 p_{1b_z} - 2p_{l_z} \tilde{A}}{2E_l p_{1b_z}}, C_x = \frac{p_{l_x} p_{1b_z} - p_{l_z} p_{1b_x}}{E_l p_{1b_z}}, C_y = \frac{p_{l_y} p_{1b_z} - p_{l_z} p_{1b_y}}{E_l p_{1b_z}},$$

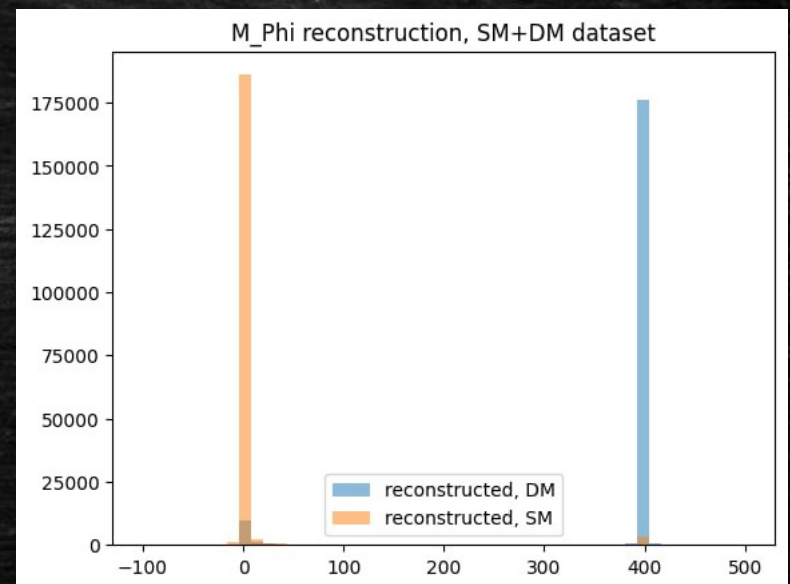
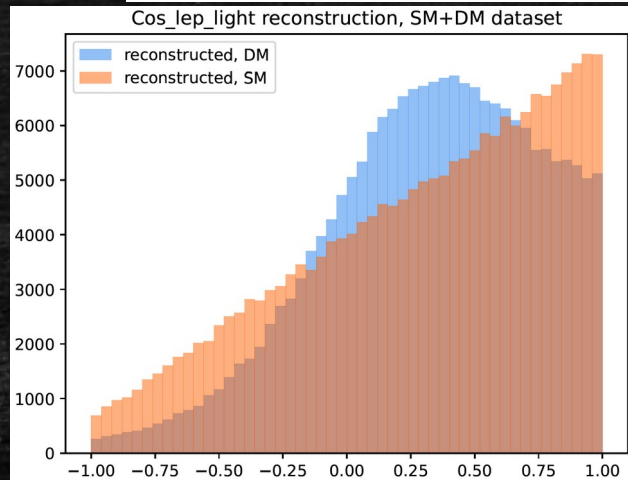
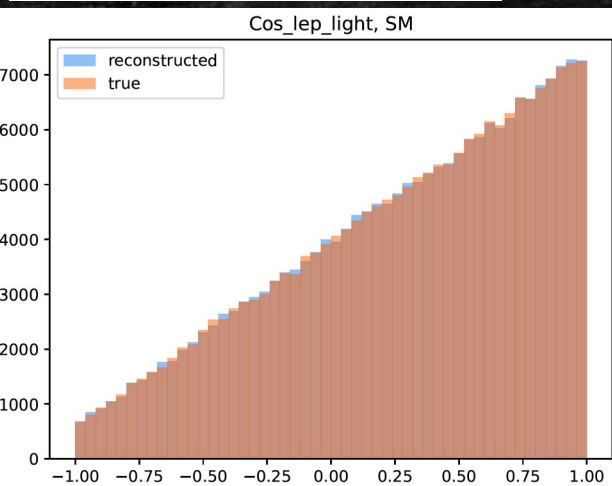
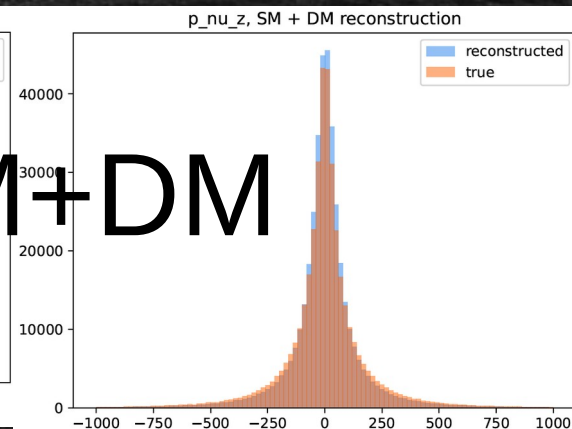
Application of Deep Neural Networks to reconstruct four-momenta of neutrino and mediator



SM



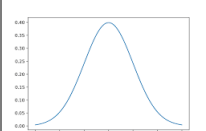
SM+DM



Метод модельно-независимого поиска отклонений от СМ. Нейронная сеть с одним классом (OCDNN)

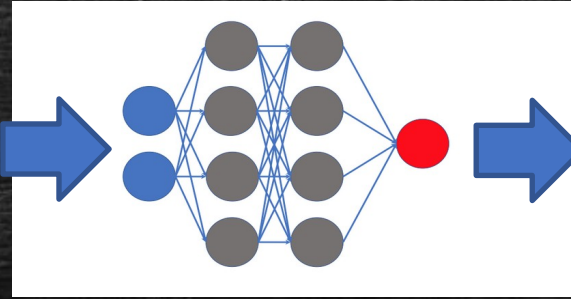
Реальные данные, СМ

Синтетический шум μ , σ



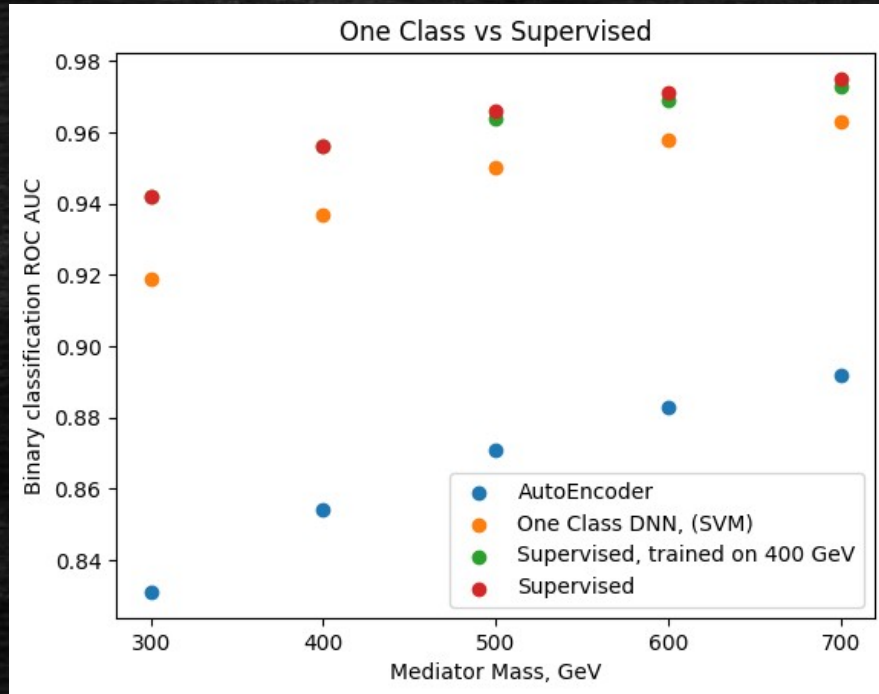
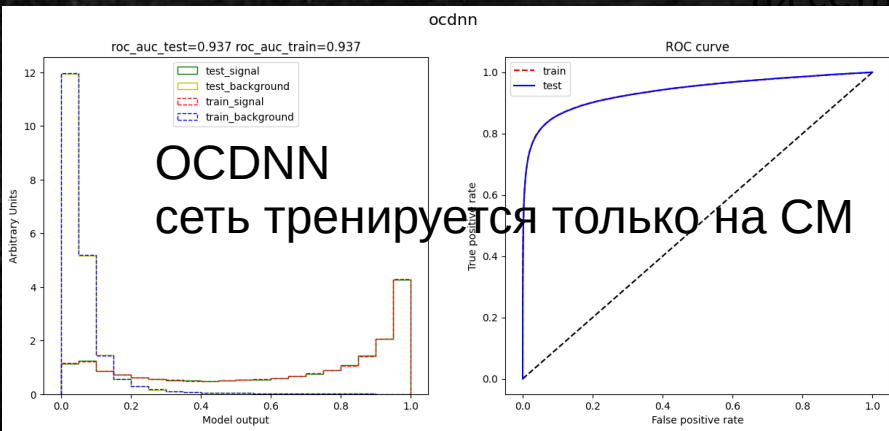
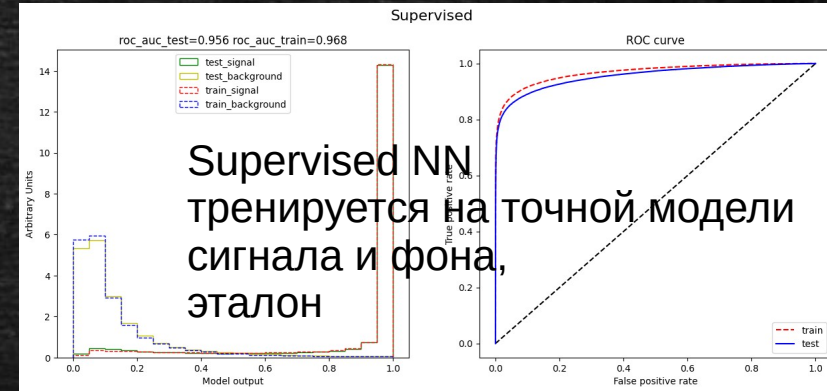
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Гиперплоскость для выделения аномалий

Нейронная сеть



Прямой поиск ТМ в процессах с топ-кварком, в разных конечных сигнатурах

lepton+jets

- $tX+M$, $tt+M$

di-lepton+jets

- $tt+M$, $tttX+M$, $tttt+M$

Same sign di-lep+jets

- $tttX+M$, $tttt+M$

3 leptons + jets

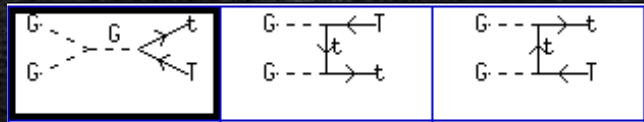
- $tttX+M$, $tttt+M$

- Моделирование всех сигнальных процессов
- Моделирование фоновых процессов для каждой сигнатуры
- Формирование наблюдаемых для каждой сигнатуры
- Проведение отдельных анализов для каждой сигнатуры и их объединение, или
- Тренировка трансформера для всех сигнатур

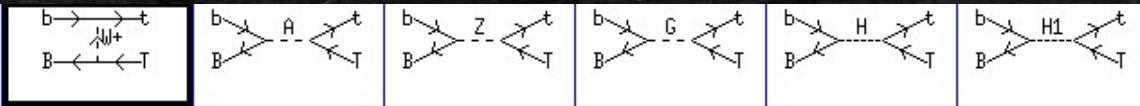
Search for DM mediator which decays to top quark pair. Fully reconstructable final state

Scalar DM mediator decay channels

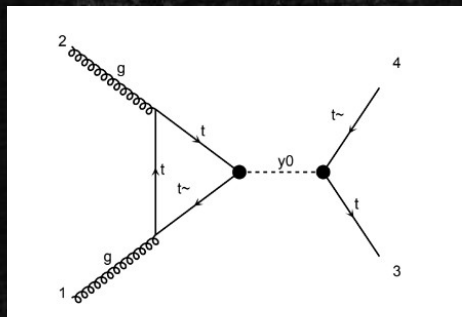
Total width : 1.905268E+01 GeV
 Modes and fractions :
 xi Xi - 84%
 b B - 0.086%
 c C - 0.0072%
 t T - 16%
 s S - 0.00017%



SM cross section [pb] = 5.3563e+02

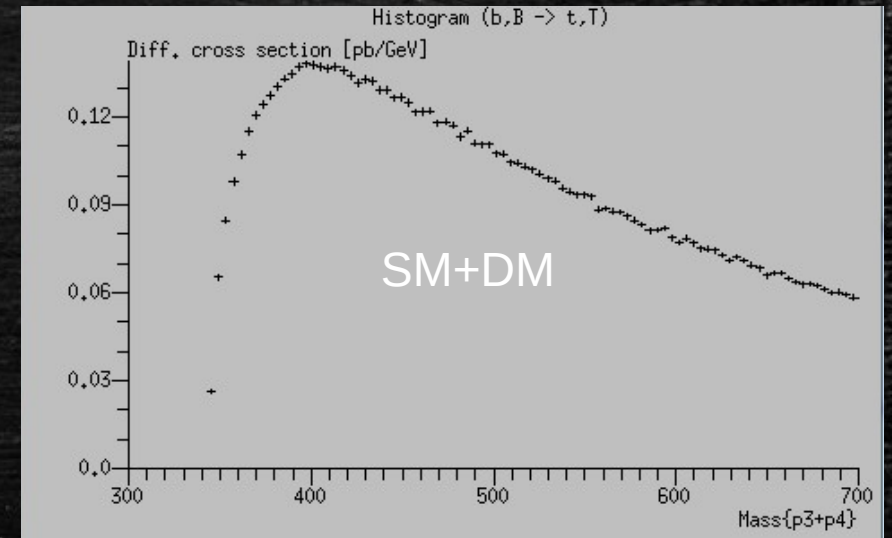
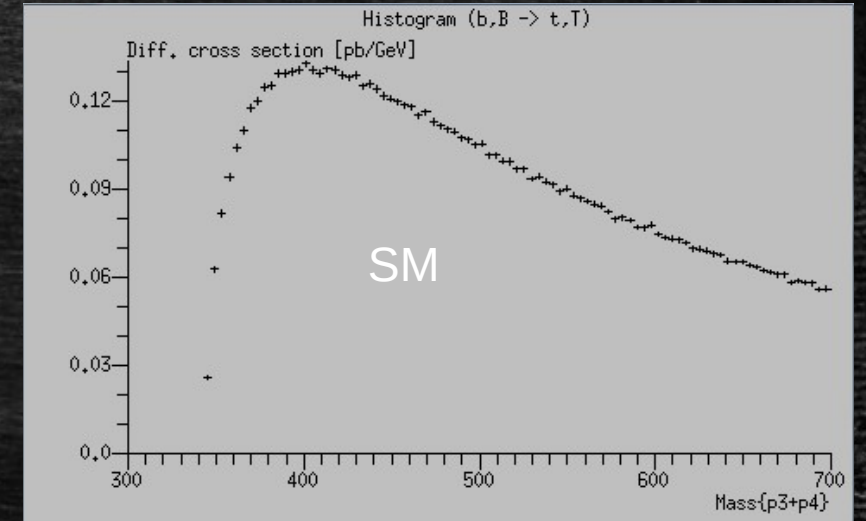


(b, B -> t, T) cross section [pb] = 1.7682e-03 (H1- DM mediator)

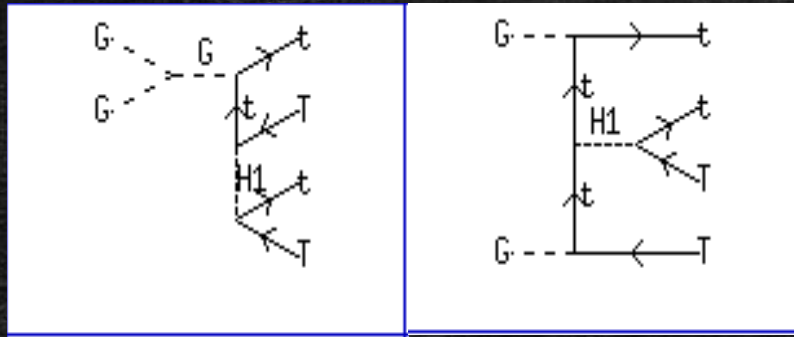


NLO TM
 cross-section : 0.88 pb
 y0 is DM mediator

CompHEP, MadGraph calculations



Search for DM mediator in the production of four top quarks. Cross check of DM contribution

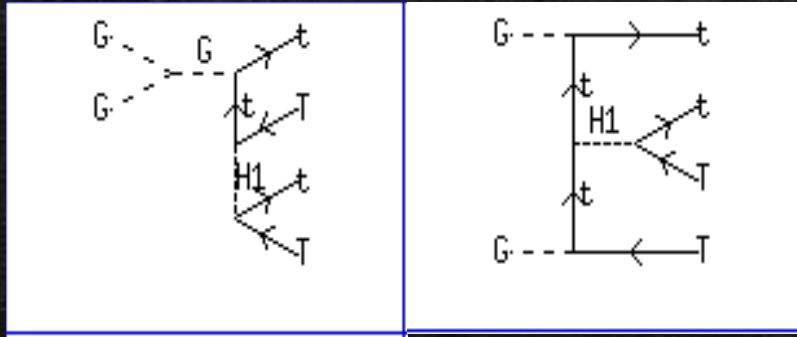


CompHEP process	CompHEP crossx (pb)	MadGraph5 process	MadGraph5 crossx (pb)
$G,G \rightarrow t,t,T,T$ (SM)	$7.7088 * 10^{-03} \pm 7.55 * 10^{-06}$	$G,G \rightarrow t,t,T,T$ QED=2 (SM)	$7.794 * 10^{-03} \pm 2.3 * 10^{-05}$
$G,G \rightarrow t,t,T,T$ (DM)	$11.152 * 10^{-03} \pm 1.60 * 10^{-05}$	$G,G \rightarrow t,t,T,T$ QED=2 NP=2 (DM)	$11.41 * 10^{-03} \pm 3.4 * 10^{-05}$
-	-	$G,G \rightarrow t,t,T,T$ QED=2 NP=3 (DM)	$11.44 * 10^{-03} \pm 3 * 10^{-05}$

Search for DM mediator in the production of four top quarks. DM loop diagrams contribution

Process description	MadGraph5 process	MadGraph5 crossx (pb)
4 top gg production in SM	$G,G \rightarrow t,t,T,T$ QED=2 (SM)	$7.794 * 10^{-03} \pm 2.3 * 10^{-05}$
Full DM without the loop diagram	$G,G \rightarrow t,t,T,T$ QED=2 NP=2 (DM)	$11.41 * 10^{-03} \pm 3.4 * 10^{-05}$
Full DM with the loop diagram	$G,G \rightarrow t,t,T,T$ QED=2 NP=3 (DM)	$11.44 * 10^{-03} \pm 3 * 10^{-05}$
DM, contribution of diagrams with the mediator without the loop diagram	$G,G \rightarrow t,t,T,T$ QED=2 NP==2 (DM)	$2.885 * 10^{-03} \pm 9.9 * 10^{-06}$
DM, contribution of loop diagrams with the mediator	$G,G \rightarrow t,t,T,T$ QED=2 NP==3 (DM)	$8.663 * 10^{-05} \pm 2.741 * 10^{-07}$

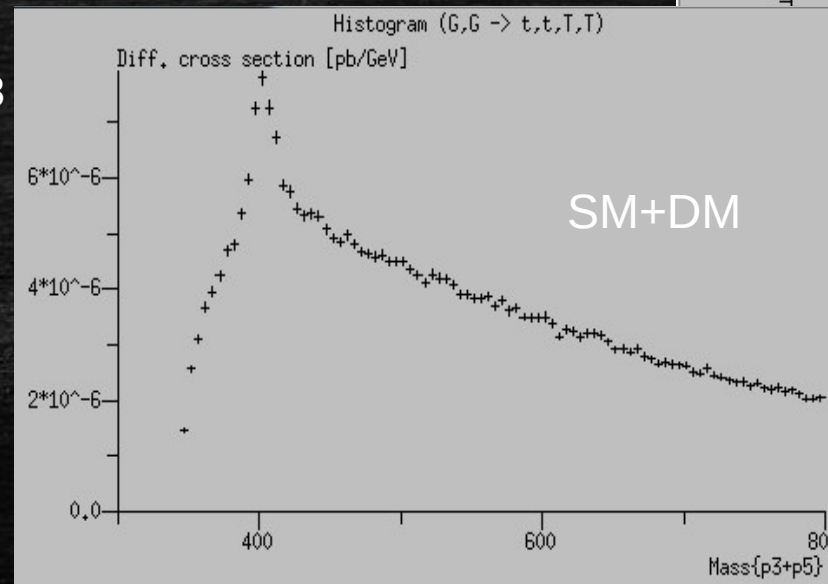
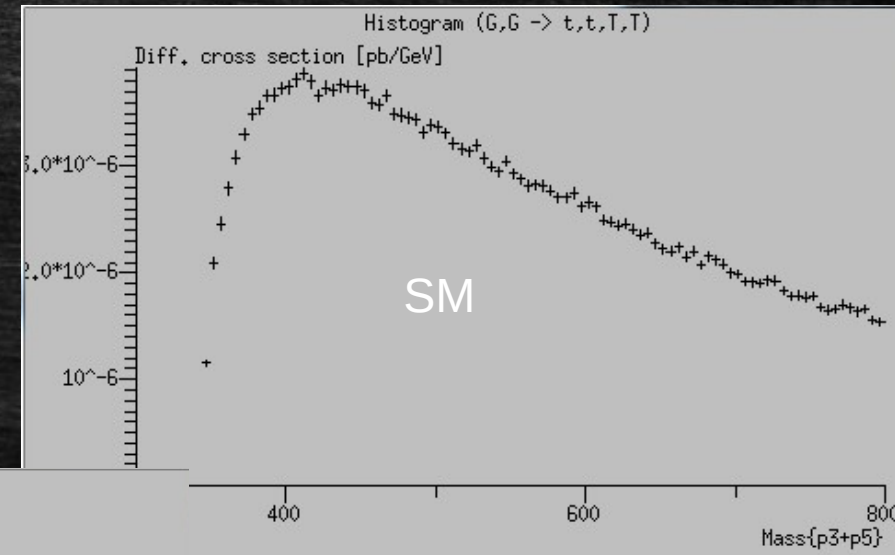
DM mediator in four top quarks production



$gg \rightarrow 4t$, SM cross section [pb] = $7.7088e-03$

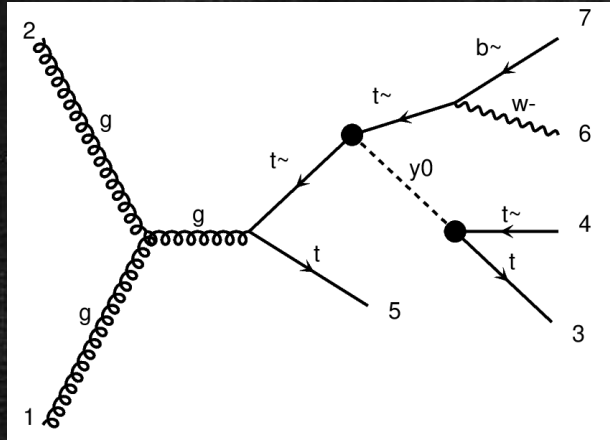
$gg \rightarrow 4t$, SM+DM cross section [pb] = $11.152e-03$

DM contribution 24%
cross section [pb] = $2.7297e-03$

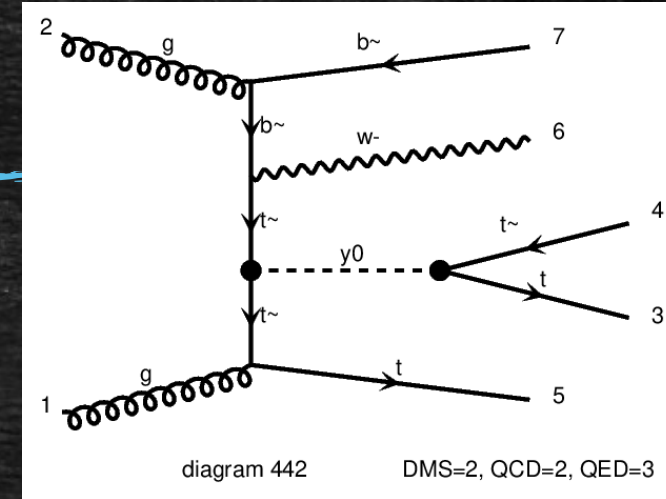


DM mediator in three top quarks production.

SM QCD,EW contributions



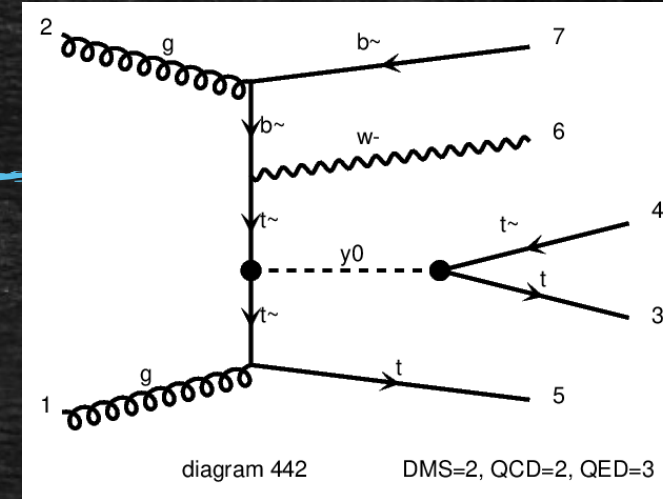
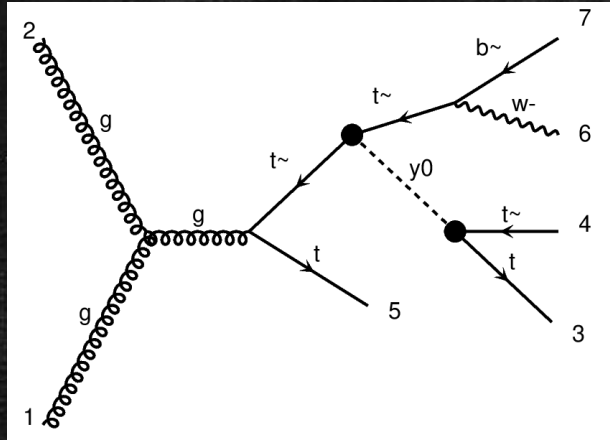
$g, g \rightarrow t, T, t, W, b$



Process description	MadGraph5 process	MadGraph5 crossx (pb)
3 top + W- B gg production in SM	$G, G \rightarrow t, t, T, W-, B$ QED=3	$15.5 * 10^{-03} \pm 4.7 * 10^{-05}$
3 top + W- B QCD contribution	$G, G \rightarrow t, t, T, W-, B$	$14 * 10^{-03} \pm 4.6 * 10^{-05}$
3 top + W- B EW contribution	$G, G \rightarrow t, t, T, W-, B$ QED==3	$6.085 * 10^{-03} \pm 1.4 * 10^{-05}$
3 top + W- pp production in SM	$p, p \rightarrow t, t, T, W-$ QED=3	$0.622 * 10^{-03} \pm 1.6 * 10^{-06}$
3 top + W- QCD contribution	$p, p \rightarrow t, t, T, W-$	$0.453 * 10^{-03} \pm 1.3 * 10^{-06}$
3 top + W- EW contribution	$p, p \rightarrow t, t, T, W-$ QED==3	$0.452 * 10^{-03} \pm 1.3 * 10^{-06}$
4 top gg production in SM	$G, G \rightarrow t, t, T, T$ QED=2	$7.794 * 10^{-03} \pm 2.3 * 10^{-05}$

DM mediator in three top quarks production.

SM QCD,EW contributions



Process description	MadGraph5 process	MadGraph5 crossx (pb)
3 top + Wb gg production in SM	$G,G \rightarrow t,t,T,W-,B$ QED=3 (SM)	$15.5 * 10^{-03} \pm 4.7 * 10^{-05}$
Full DM without the loop diagram	$G,G \rightarrow t,t,T,W-,B$ QED=3 NP=2 (DM)	$23.02 * 10^{-03} \pm 6.2 * 10^{-05}$
Full DM with the loop diagram	$G,G \rightarrow t,t,T,W-,B$ QED=3 NP=3 (DM)	$23.16 * 10^{-03} \pm 6 * 10^{-05}$
DM, contribution of diagrams with the mediator without the loop diagram	$G,G \rightarrow t,t,T,W-,B$ QED=3 NP==2 (DM)	$6.033 * 10^{-03} \pm 1.2 * 10^{-05}$
DM, contribution of loop diagrams with the mediator	$G,G \rightarrow t,t,T,W-,B$ QED=3 NP==3 (DM)	$1.719 * 10^{-04} \pm 5 * 10^{-07}$

Search for DM mediator in the production of three and four top quarks. Interference contribution

SM LO three top quarks production

tt(t)tW	subprocess	Cross section [pb]
1	$\bar{b}, g \rightarrow W^+, t, \bar{t}, \bar{t}$	3.40e-04
2	$b, g \rightarrow W^-, t, t, \bar{t}$	3.40e-04
G	Sum of gluon diags.	1.01e-03
EW	Sum of EW diags.	0.962e-03
Int	Interference	-0.612e-03
	Total cross section	1.36e-03

g,g -> t, T, t, W, b
 MadGraph calculatitons
 3-top-quarks tree NLO + 4-top-quarks:

2107.07629

Standard Model:

Sum of gluon diags. 14.22e-03 pb
 Sum of EW diags. 6.19e-03 pb
 Total cross section 15.77e-03 pb
 Interference - 4.64e-03 pb

Simplified DM scalar mediator+SM

Sum of gluon diags. 14.22e-03 pb
 Sum of EW diags.. 16.25 e-03 pb
 Total cross section 24.69e-03 pb
 Interference -5.78 e-03 pb

DM contribution 36%

DM cross section [pb] = 8.9e-03 +- 6.8e-05 pb

Conclusion

- Top quark production processes are very interesting for DM search
- New observable has proposed to distinguish DM and SM contribution. It is based on well known SM spin correlations which are absent or different in DM contribution
- New model independent NN approach has proposed to search for deviations from SM. NN is trained only on the SM events (properties).
- Three and four top quark production processes are very interesting to search for DM mediator which decays to top quark pair. Interference effects have to be taken into account.