Efim Fradkin Centennial Conference

Lebedev Institute / September 2-6, 2024

Search for Dark Matter with top quark production processes at modern colliders

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

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Theory models

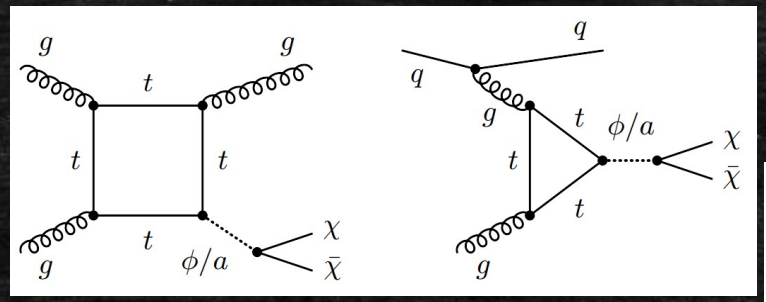
1506.03116

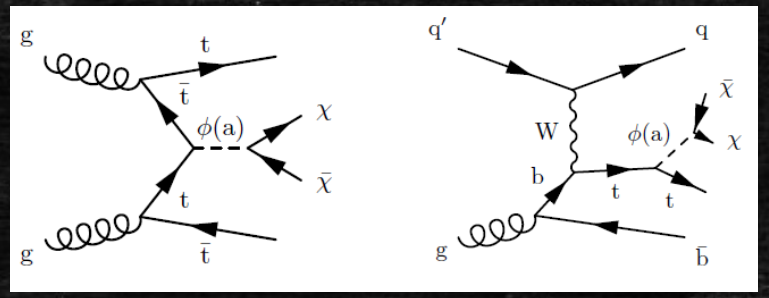
- Simplified models is all we need to model top quark interections with DM sector, for a while
- Search in:
  - Associated production of top quark and DM;
  - Top quark pair is produced in the decay of DM mediator
- Mostly does not depend on DM mass ($2m_\chi < m_\Phi$), quadratically depends on coupling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

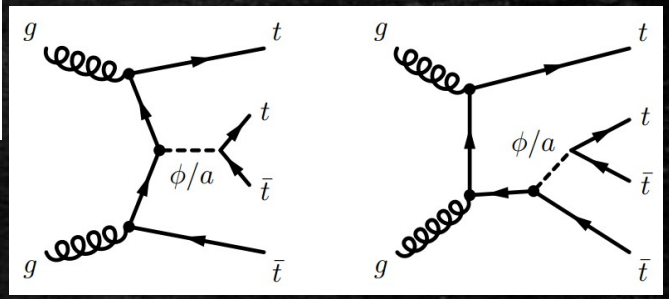
$$L_\Phi = g_\chi \Phi \bar{\chi}\chi + \frac{g_v \Phi}{\sqrt{2}} \sum_f \left(y_f \bar{f} f\right)$$

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

$$\mathcal{L}_{\text{fermion},V} \supset V_\mu \bar{\chi}\gamma^\mu (g_\chi^V - g_\chi^A \gamma_5)\chi + \sum_{f=q,\ell,\nu} V_\mu \bar{f}\gamma^\mu (g_f^V - g_f^A \gamma_5) f$$

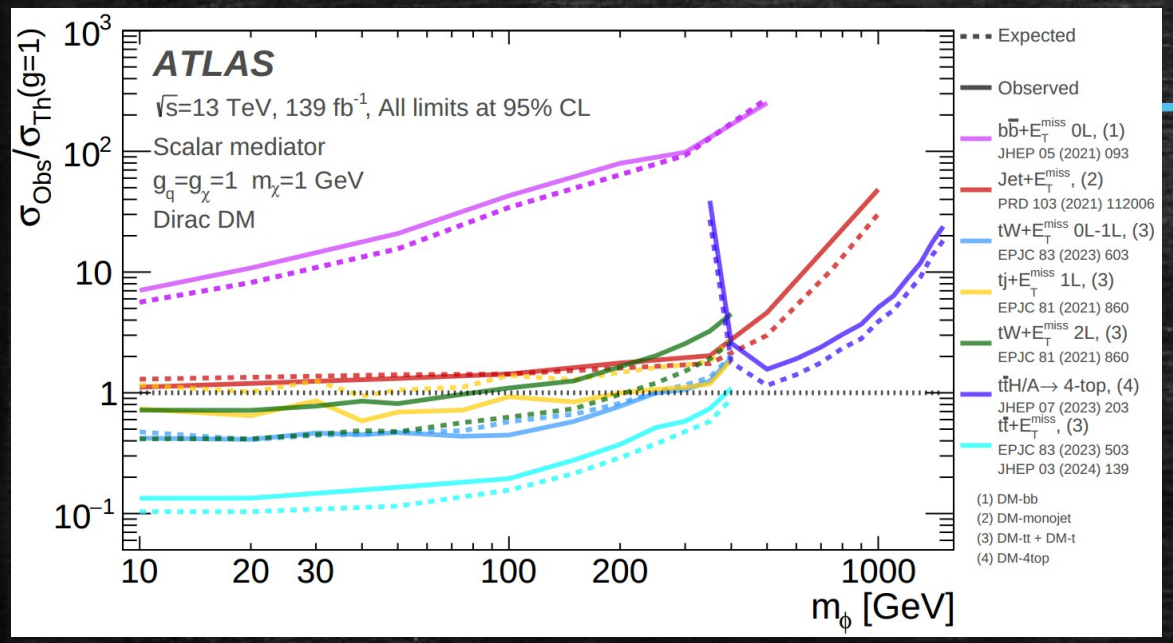


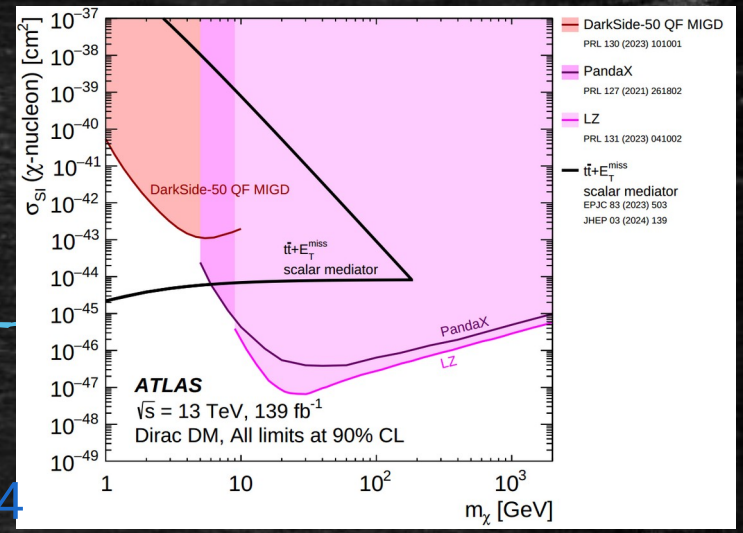




$$\{m_\chi,\ m_{\phi/a},\ g_\chi,\ g_u,\ g_d,\ g_\ell\}$$

Experimental limits





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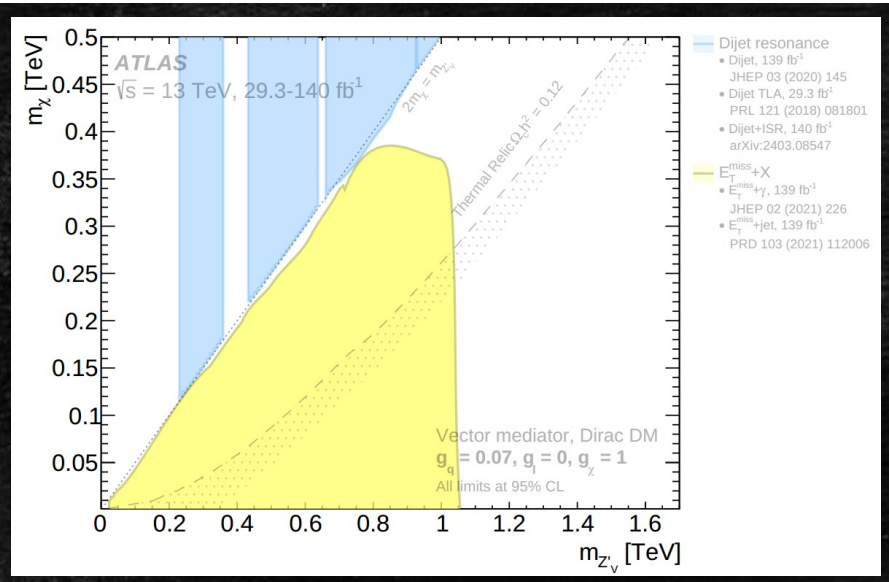

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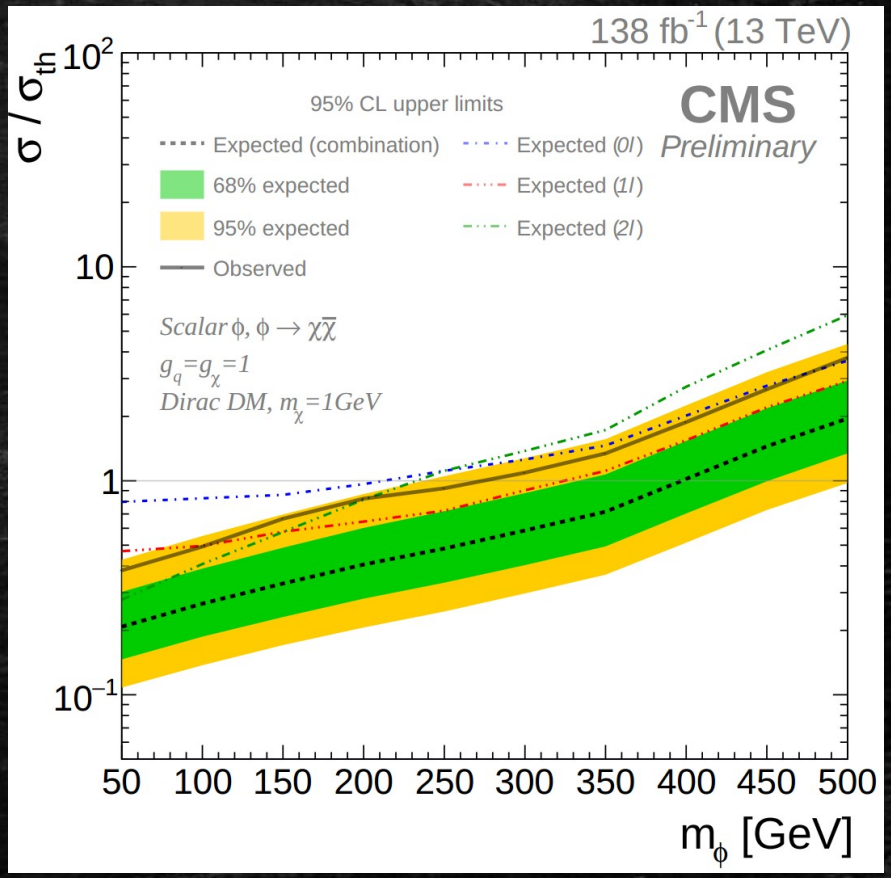
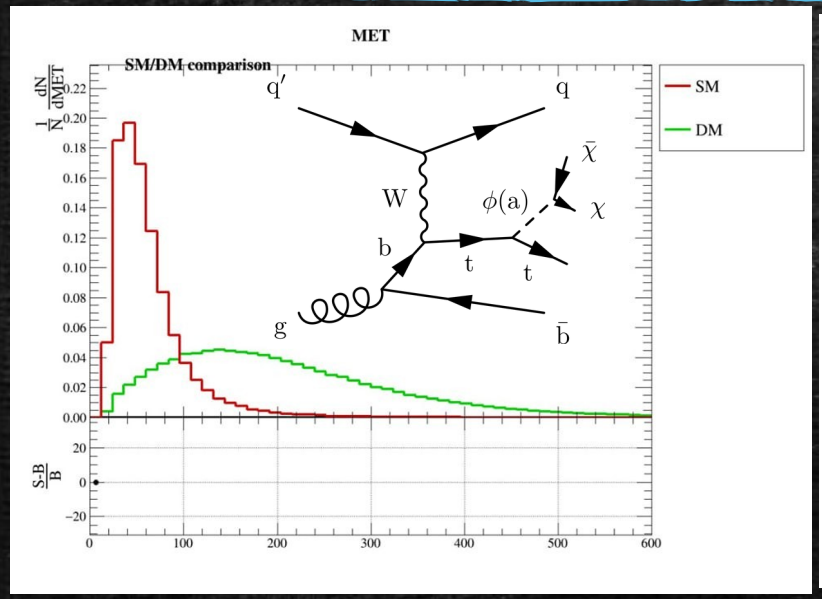
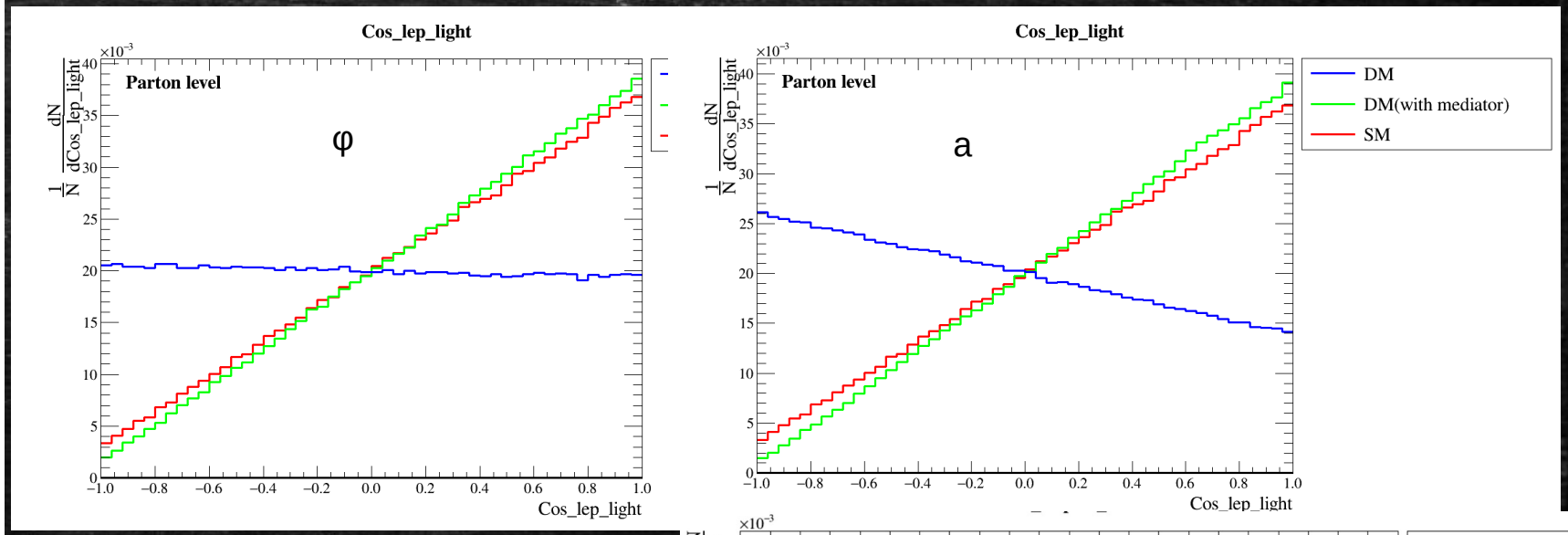


Search methodology and observables.





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.

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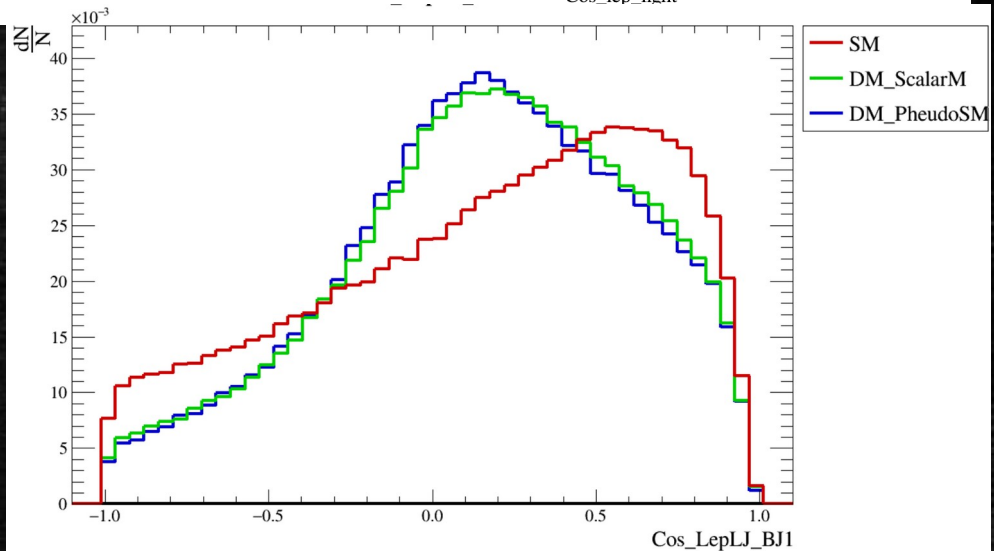

Attempt to distinguish analytically neutrino and mediator momentum

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

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

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

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

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

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

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

$$d = \frac{\tilde{C_{xy}^2} - \tilde{C_{x^2}}\tilde{C_{y^2}}}{\tilde{C_{x^2}}^2}, e = \frac{2\tilde{C_{xy}}\tilde{C_x} - 2\tilde{C_{x^2}}\tilde{C_y}}{\tilde{C_{x^2}}^2}, f = \frac{\tilde{C_x^2} - \tilde{C}\tilde{C_{x^2}}}{\tilde{C_{x^2}}^2}$$

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

$$\tilde{C_{xy}} = C_xC_y - \frac{p_{1b_x}p_{1b_y}}{p_{1b_z}^2}, \tilde{C_x} = CC_x - \frac{\tilde{A}p_{1b_x}}{p_{1b_z}^2}, \tilde{C_y} = CC_y - \frac{\tilde{A}p_{1b_y}}{p_{1b_z}^2}$$

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

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

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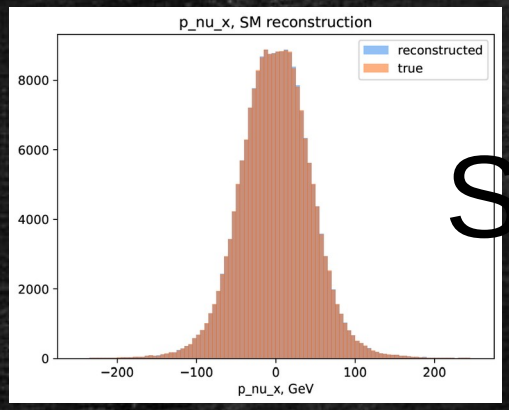
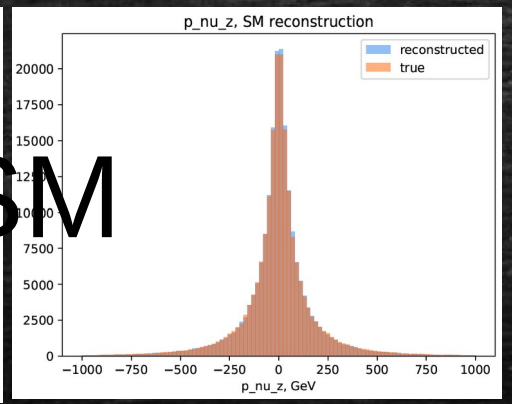
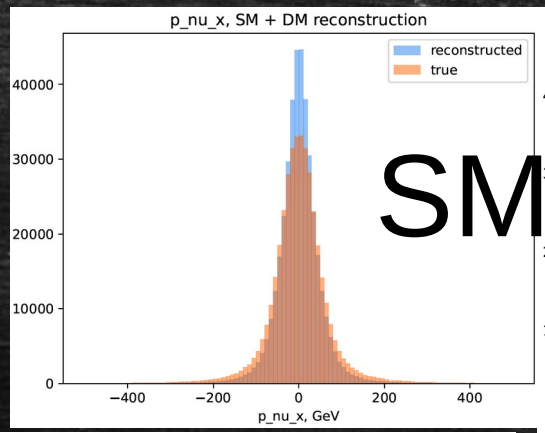
Application of Deep Neural Networks to reconstruct four-momenta of neutrino and mediator

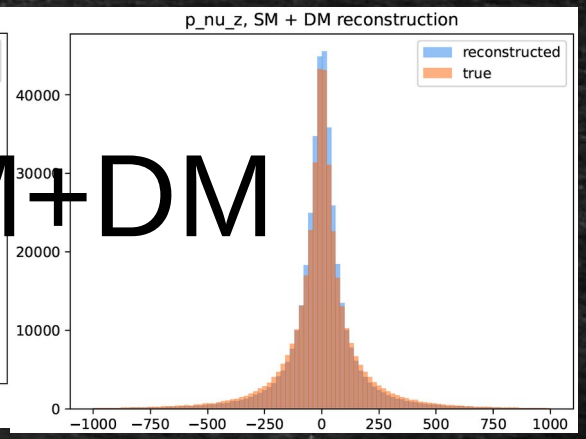
SM

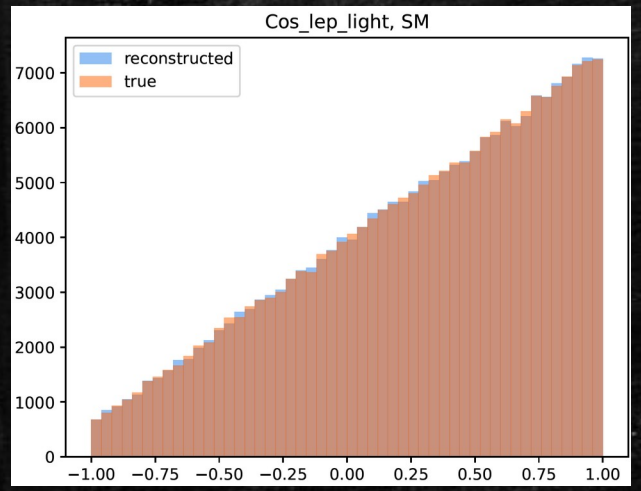
SM+DM

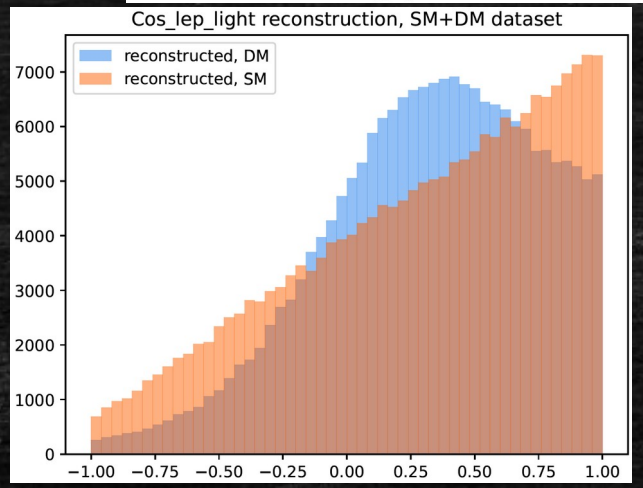


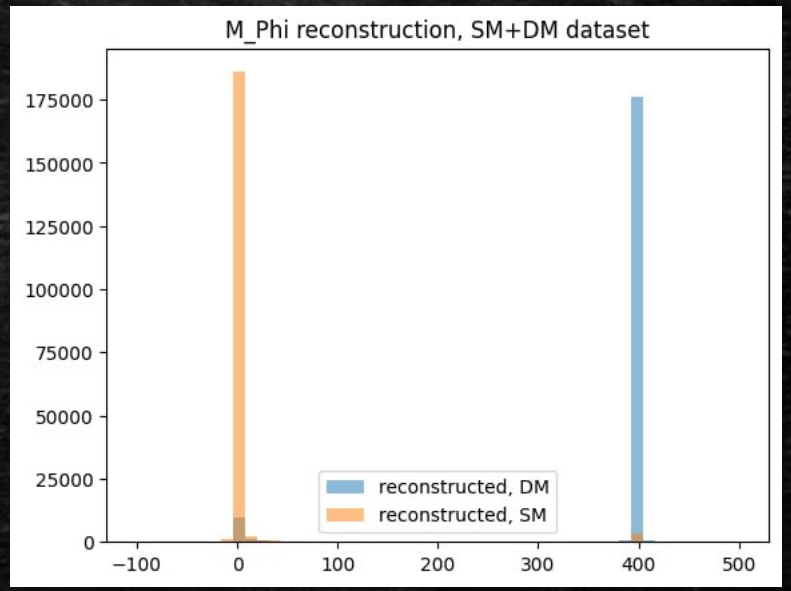












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Application of Kolmogorov Arnold Networks (KAN) to reconstruct four-momenta of neutrino and mediator

2404.19756

Multi-Layer Perceptron (MLP)	Kolmogorov-Arnold Network (KAN)
Universal Approximation Theorem	Kolmogorov-Arnold Representation Theorem
$f(\mathbf{x}) \approx \sum_{i=1}^{N(\epsilon)} a_i \sigma(\mathbf{w}_i \cdot \mathbf{x} + b_i)$	$f(\mathbf{x}) = \sum_{q=1}^{2n+1} \Phi_q \left(\sum_{p=1}^{n} \phi_{q,p}(x_p) \right)$
(a) *fixed* activation functions on *nodes*; *learnable* weights on *edges*	(b) *learnable* activation functions on *edges*; sum operation on *nodes*

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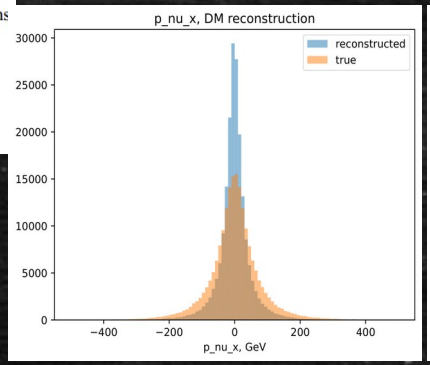
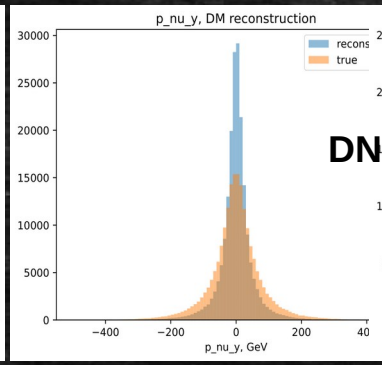
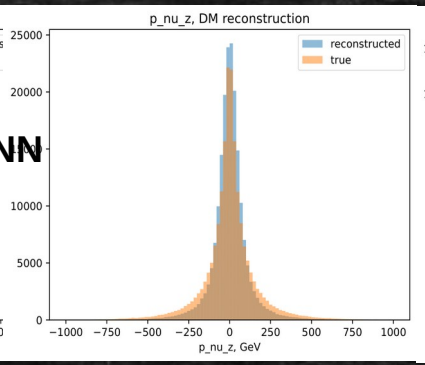
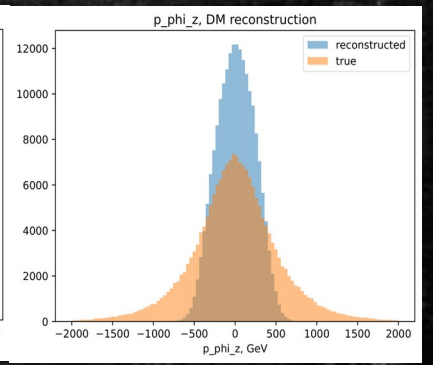
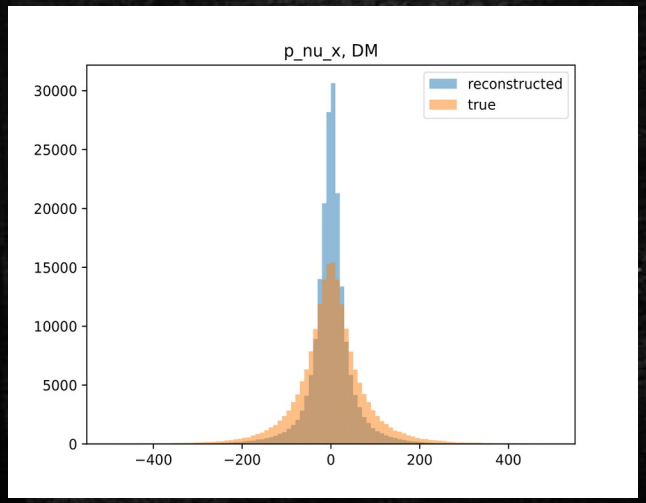




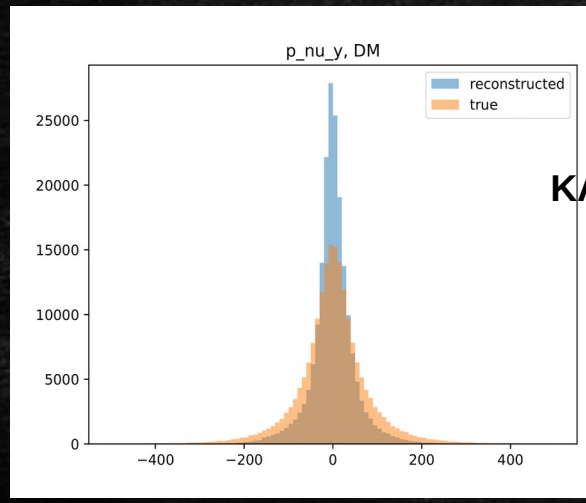
DNN

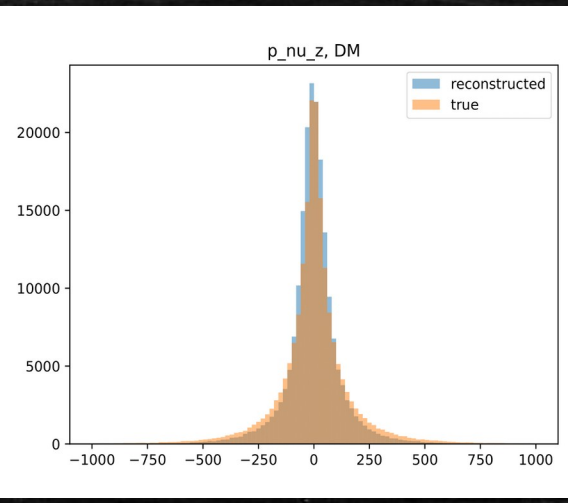


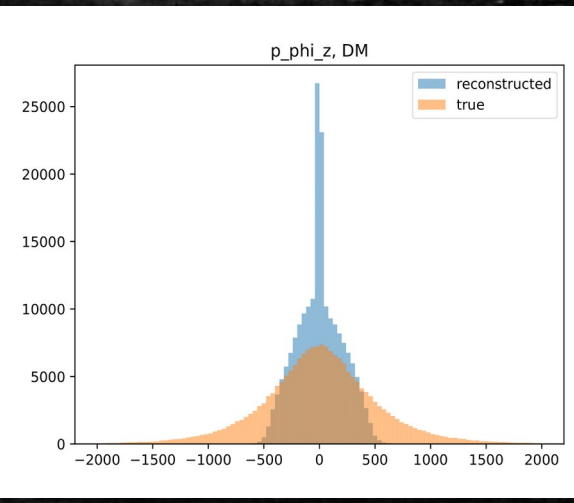




KAN



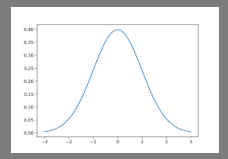




Метод модельно-независимого поиска отклонений от СМ. Нейронная сеть с одним классом (OCDNN)

Реальные данные, СМ

Синтетический шум
Mu, Sigma



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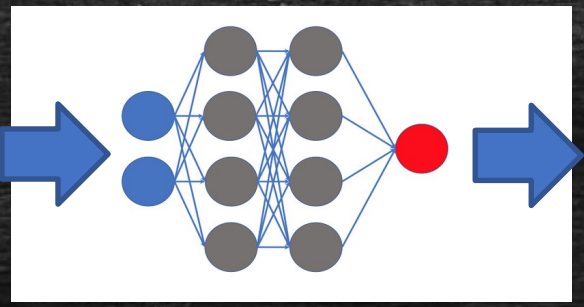
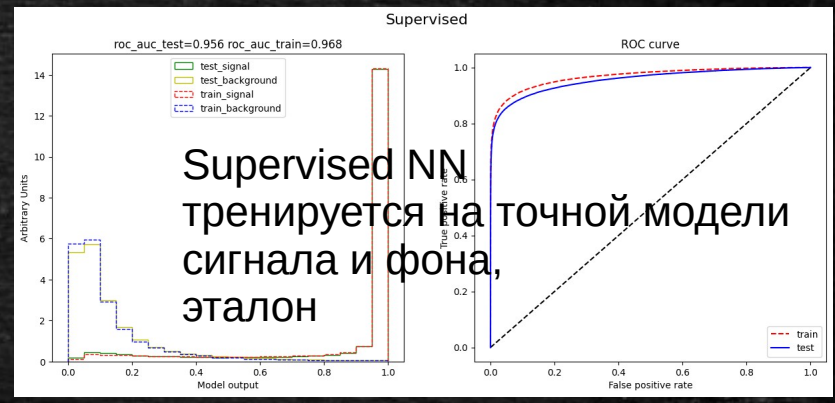
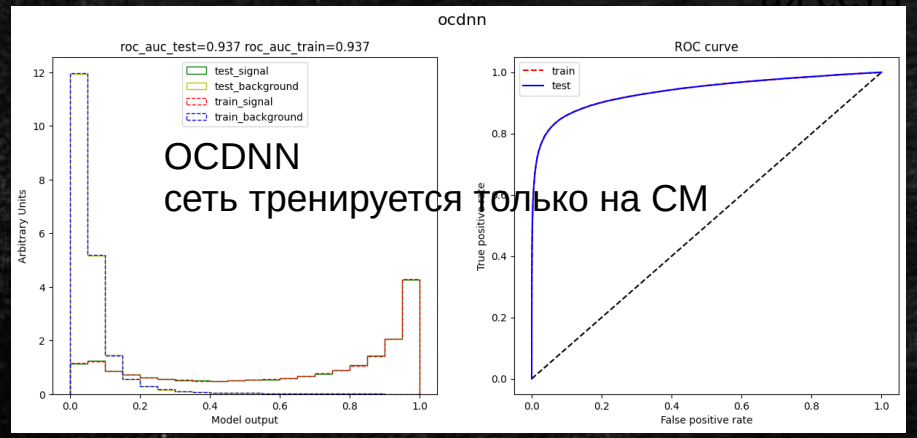


Гиперплоскость для выделения аномалий

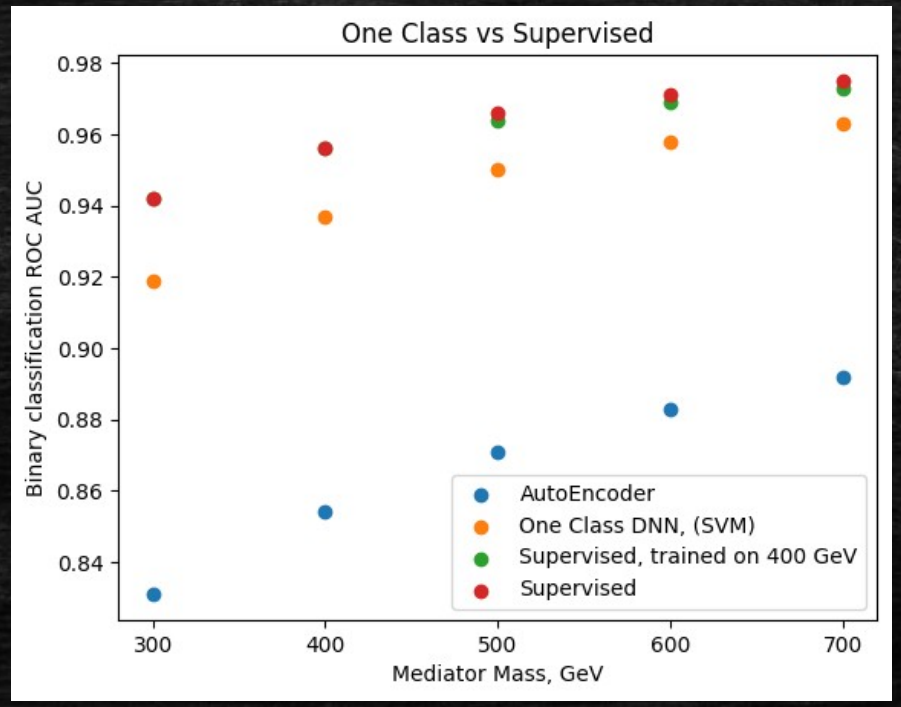
Нейронная сеть



Supervised NN тренируется на точной модели сигнала и фона, эталон



OCDNN
сеть тренируется только на СМ



Moscow University Physics Bulletin, 2023, Vol. 78, No. 7, pp. 80–84. **DOI:** 10.3103/S0027134923070329

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

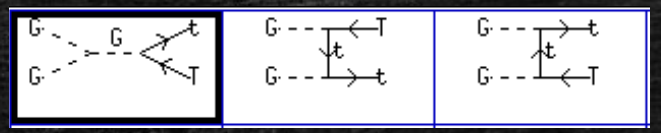
- Моделирование всех сигнальных процессов
- Моделирование фоновых процессов для каждой сигнатуры
- Формирование наблюдаемых для каждой сигнатуры
- Проведение отдельных анализов для каждой сигнатуры и их обьединение, или
- Тренировка трансформера для всех сигнатур

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

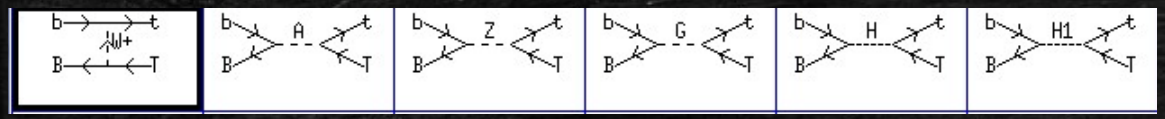
2407.08308

Scalar DM mediator decay channels

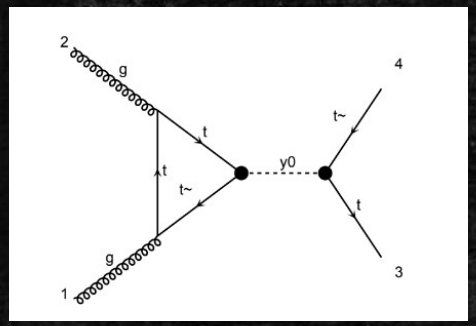
```
Total width :  1.905268E+01 GeV
Modes and fractions :        xi Xi -      84%        t T -      16%
b B -    0.086%              c C -    0.0072%      s S -    0.00017%
```



SM cross section [pb] = 5.3563e+02

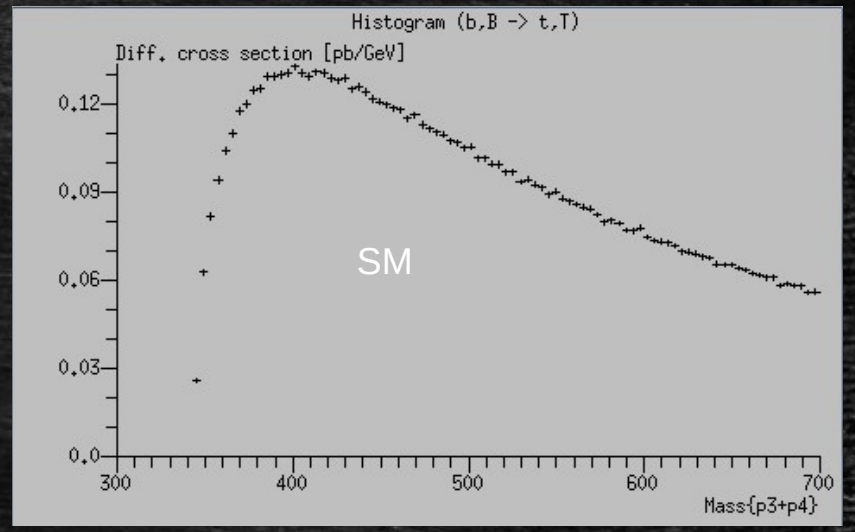


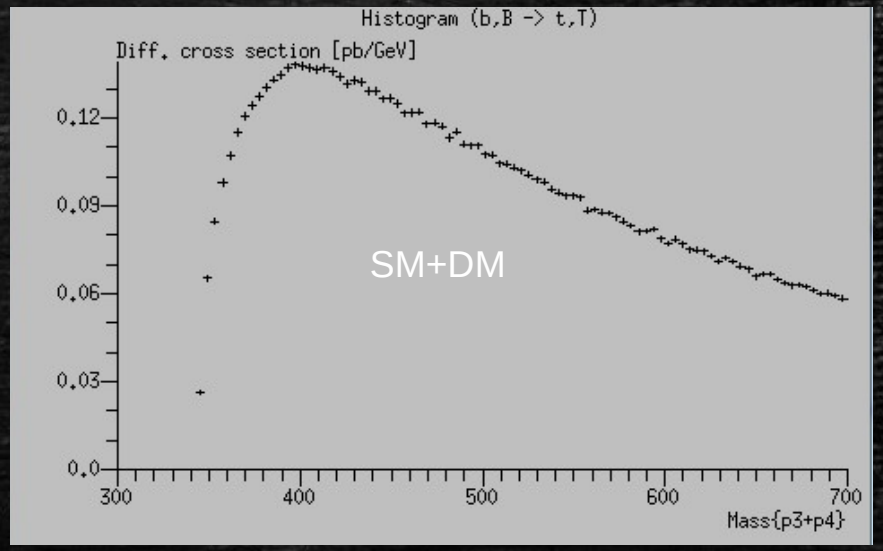
(b,B -> t,T) cross section [pb] = 1.7682e-03 (H1- DM mediator)



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

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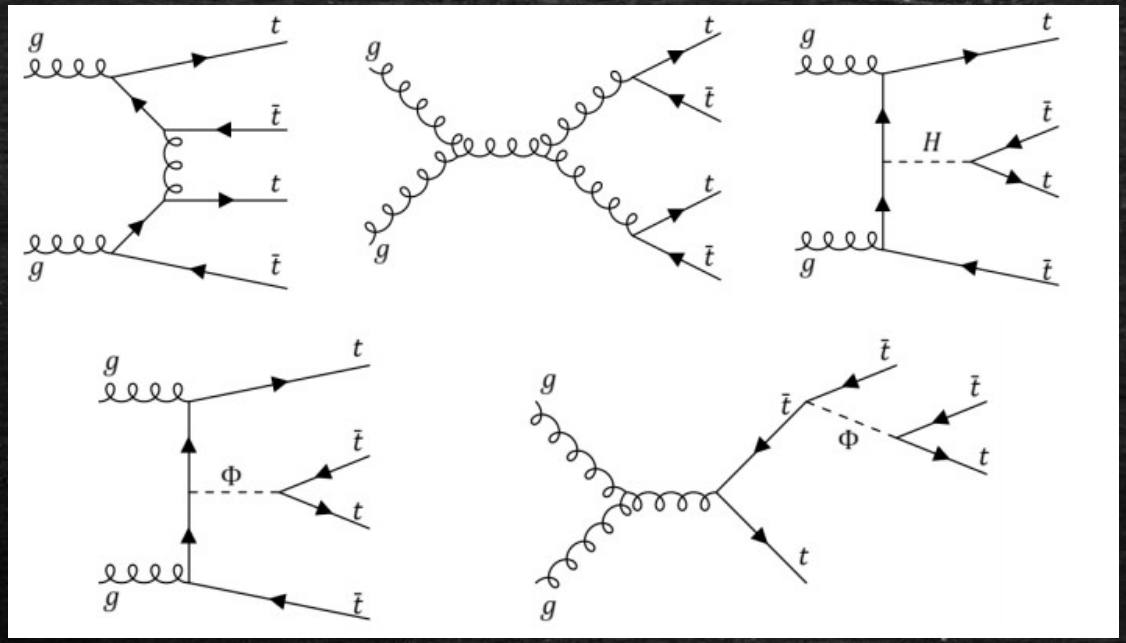

Process	CompHEP Cross-section (fb)	MadGraph Cross-section (fb)
$gg \to t\bar{t}t\bar{t}$ (SM)	$7.71 \pm 7.55 * 10^{-3}$	$7.79 \pm 2.3 * 10^{-2}$
$gg \to t\bar{t}t\bar{t}$ (SM + DM)	$11.15 \pm 1.60 * 10^{-2}$	$11.41 \pm 3.4 * 10^{-2}$

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

2407.08308

Description of the process $gg \to t\bar{t}t\bar{t}$ (DM)	MadGraph Cross-section (fb)
Full set of diagrams, including loop diagrams	$11.44 \pm 3 * 10^{-2}$
Contribution of diagrams with a mediator, excluding loop diagrams	$2.89 \pm 9.9 * 10^{-3}$
Contribution of loop diagrams with a mediator	$8.67 * 10^{-2} \pm 2.74 * 10^{-4}$

DM mediator in four top quarks production

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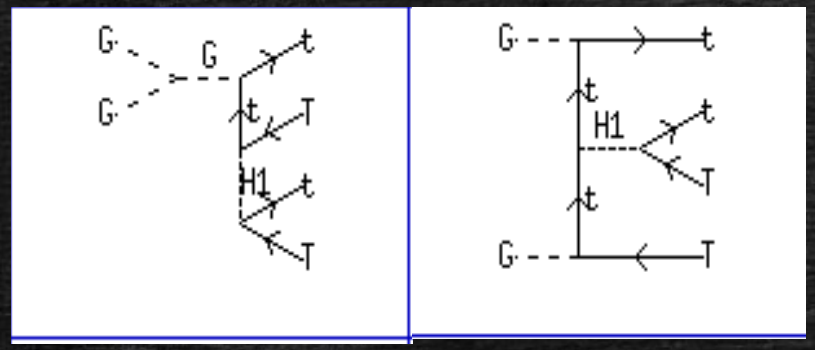
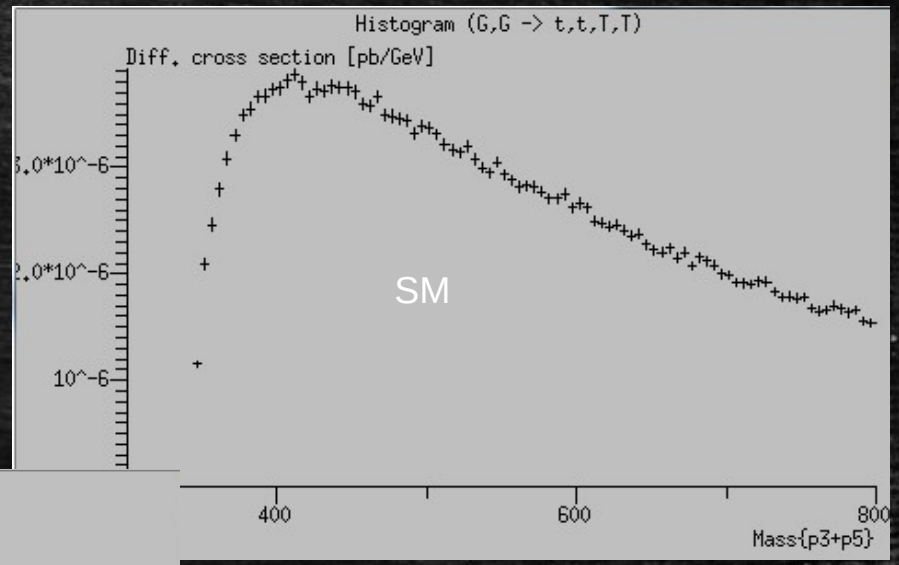
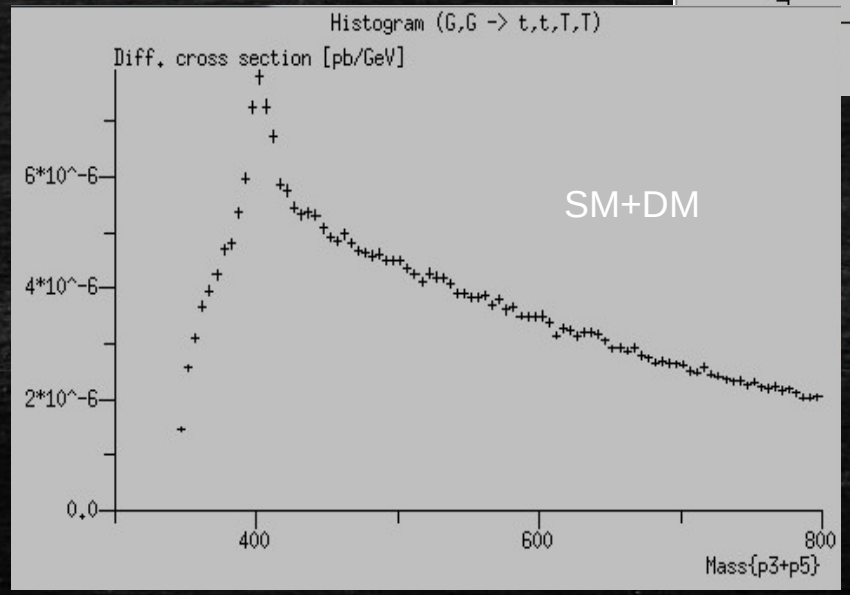


gg-> 4t, SM cross section [fb] = 7.79

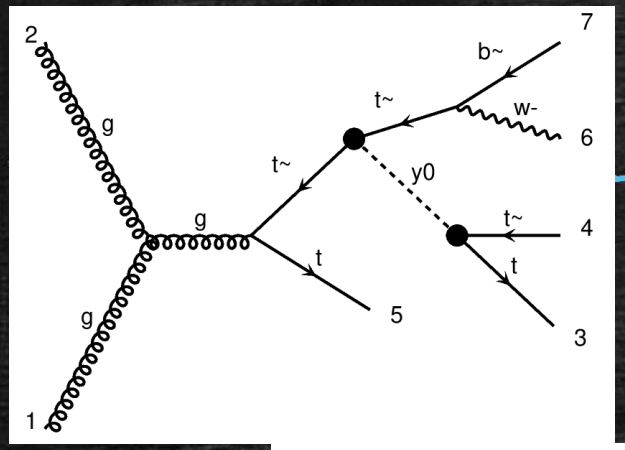
gg->4t, SM+DM cross section [pb] = 11.44

DM contribution 32%
cross section [fb] = 3.65

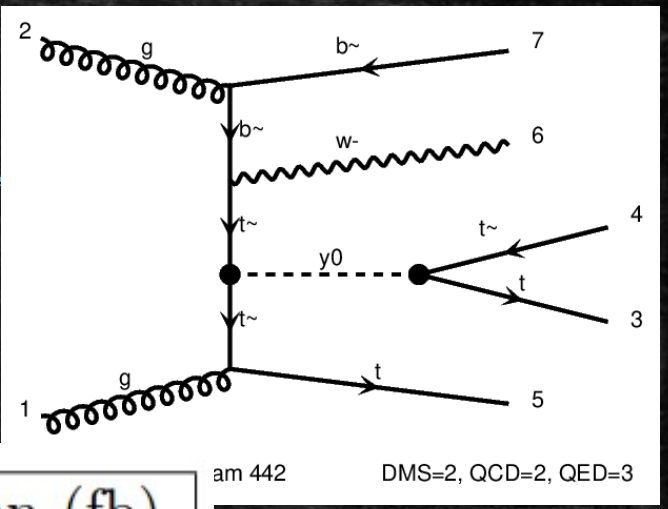




DM mediator in three top quarks production.
SM QCD,EW contributions



g,g -> t, T, t, W, b



am 442 DMS=2, QCD=2, QED=3

2107.07629

Process Description	MadGraph Cross-section (fb)
$pp \to t\bar{t}tW^-$, QCD+EW	$0.622 \pm 1.6 * 10^{-3}$
$pp \to t\bar{t}tW^-$, QCD	$0.453 \pm 1.3 * 10^{-3}$
$pp \to t\bar{t}tW^-$, EW	$0.452 \pm 1.3 * 10^{-3}$
$pp \to t\bar{t}tW^-$, QCD+EW+DM	$1.54 \pm 5 * 10^{-3}$
$gg \to t\bar{t}tW^-\bar{b}$, QCD+EW	$15.5 \pm 4.7 * 10^{-2}$
$gg \to t\bar{t}tW^-\bar{b}$, QCD	$14.0 \pm 4.6 * 10^{-2}$
$gg \to t\bar{t}tW^-\bar{b}$, EW	$6.08 \pm 1.4 * 10^{-2}$
$gg \to t\bar{t}tW^-\bar{b}$, QCD+EW+DM	$23.02 \pm 6 * 10^{-2}$

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

2407.08308

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

Process $gg \to t\bar{t}tW^-\bar{b}$	MadGraph Cross-section (fb)
Full set of diagrams in the SM	$15.55 \pm 4.7 * 10^{-2}$
Full set of diagrams in the DM model, excluding loop diagrams	$23.02 \pm 6.2 * 10^{-2}$
Full set of diagrams in the DM model, including loop diagrams	$23.16 \pm 6 * 10^{-2}$
Contribution of diagrams with a DM mediator, excluding loop diagrams	$6.03 \pm 1.2 * 10^{-2}$
Contribution of loop diagrams with a DM mediator	$0.17 \pm 5 * 10^{-4}$

Standard Model:

Sum of gluon diags. 14 fb
Sum of EW diags. 6 fb
Total cross section 15.5b
Interference - 4.5 fb

Simplified DM scalar mediator+SM

Total cross section 23 fb
SM contribution 15.5 fb
DM contribution 7.5 fb

DM contribution: 33% with benchmark couplings and m_mediator = 400 GeV

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.