Separation of different top quark production processes in a phase space using Neural Networks

E. Boos, V. Bunichev, L. Dudko,
M. Perfilov, P. Volkov, G. Vorotnikov

Scobeltsyn Institute of Nuclear Physics
Lomonosov Moscow State University (SINP MSU)

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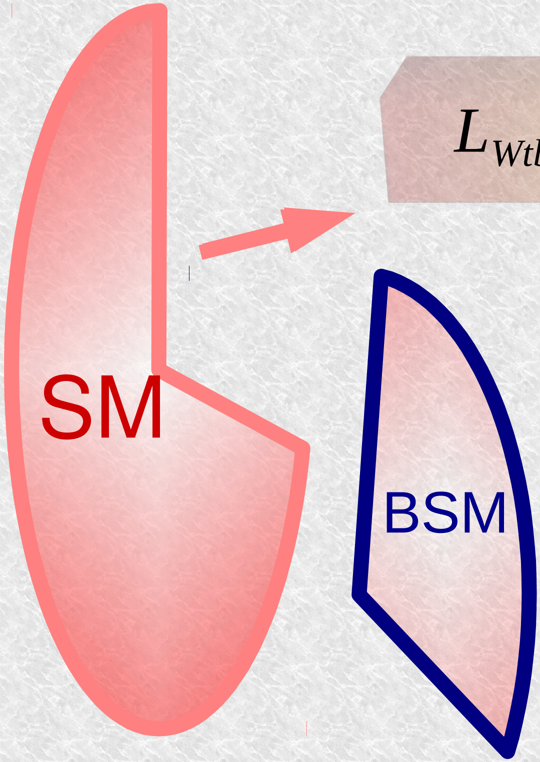
Outline

- Single and double resonant top quark production with the same final signature *tWb*
  - *schemes of single resonant top quark highlighting*
  - *Preference of using the full tWb scheme*
  - *Separation between SR and DR top quark production in phase space with DNN*

- Anomalous Wtb couplings searches in tWb final state
  - *preliminary results of separation between anomalous contributions in (LV, RV) scenario*

- Triple and Quadruple resonant top quark production with the same final signature tttWb

Top quark and BSM physics



$$L_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \bar{b} \gamma^{\mu} \frac{1}{2} \cdot 1 \cdot (1-\gamma_5) t W_{\mu}$$

Deviations from the SM:

New particles in the single top production

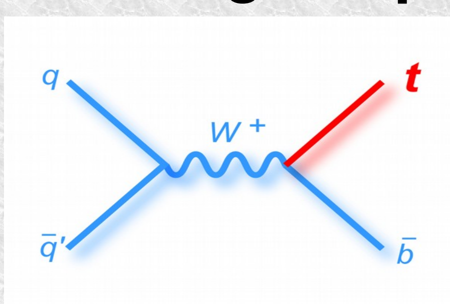
→ W'

Modification of predicted by the SM values of top couplings to another particles

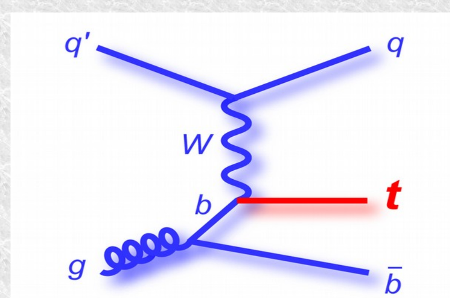
→ Anomalous Wtb couplings

→ FCNC

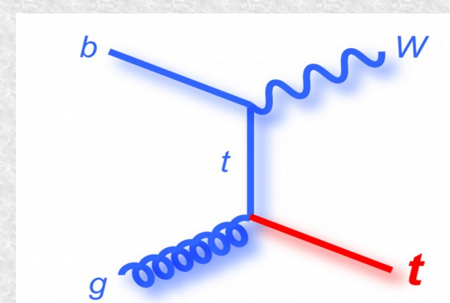
Single top quark production processes



s-channel

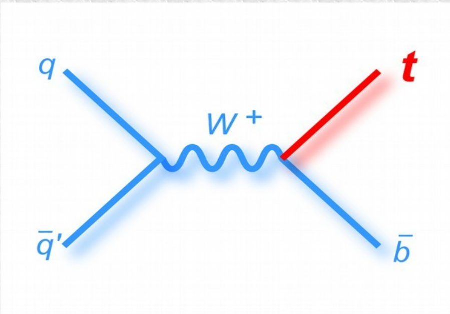
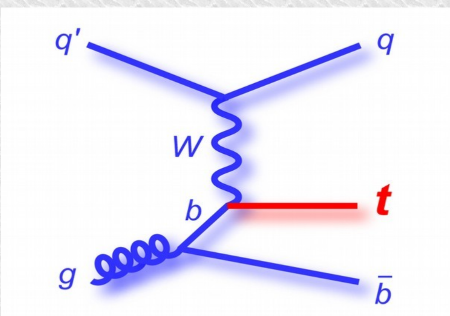
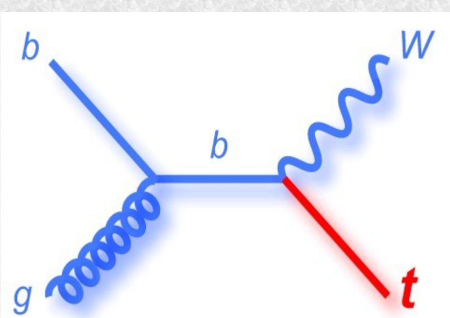


t-channel



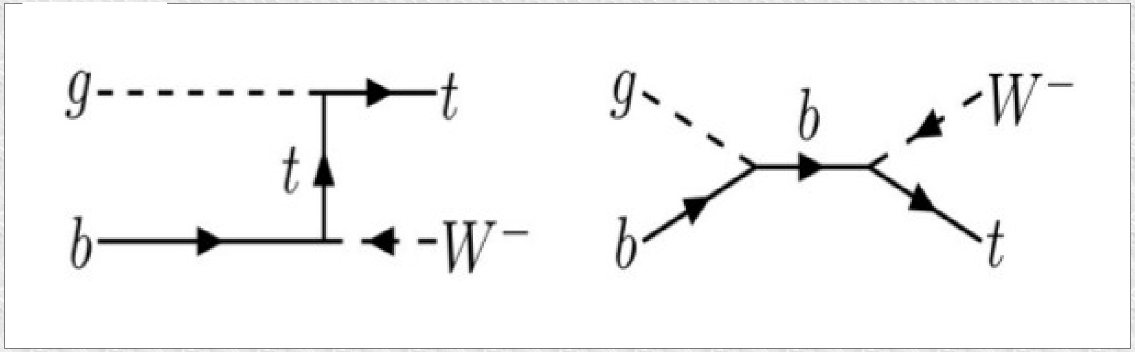
tW-channel

Single Top quark production CSs

	Tevatron	LHC 8 TeV	LHC 13 TeV	LHC 14 TeV	Current status
s-channel 	1.05	5.24	10.32	11.39	Tevatron s-channel observation
t-channel 	2.08	84.69	217	248	TEVATRON observation CMS CS measurement ATLAS CS Measurement
tW production 	0.28	22.37	71.7	84.4	CMS Observation @8TeV ATLAS and CMS combination

Top pair and Single Top production

- Leading order (**LO**) process 2→2: **tW**-production



- Next to leading order (**NLO**), O(1/log(mt/mb)), 2→3: **tWb-production**

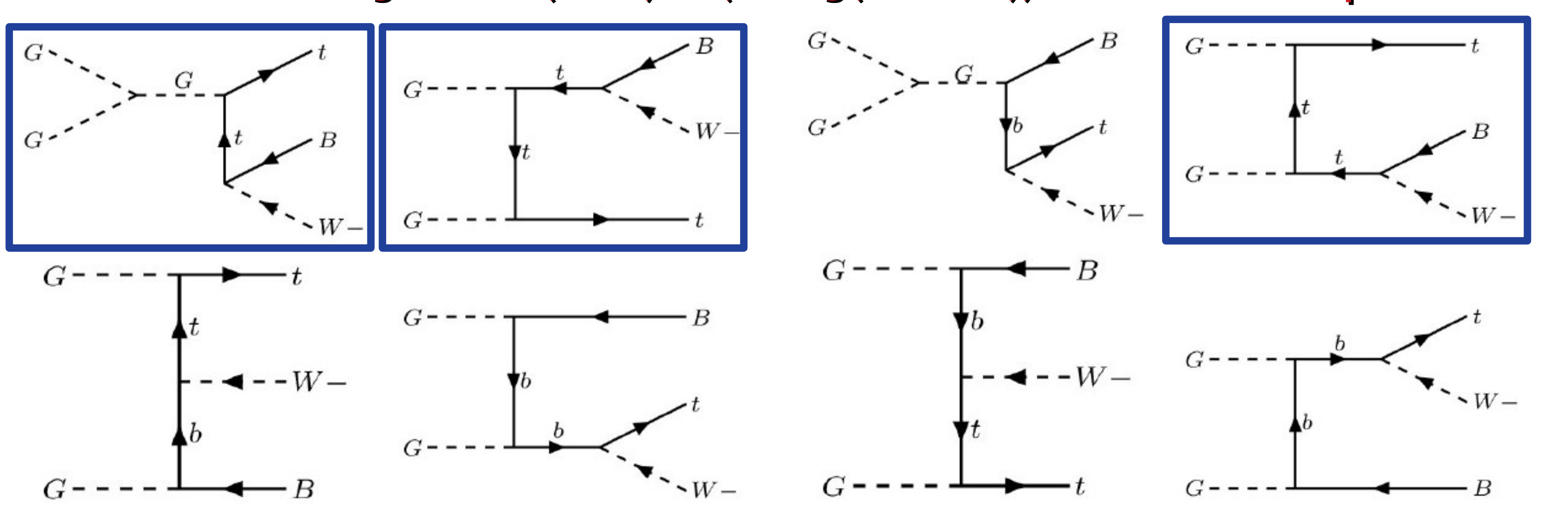
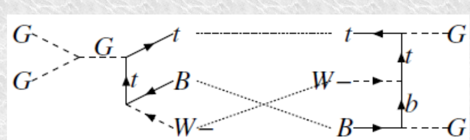


Figure 1: Diagrams for the process $gg \to t\bar{b}W^-$.

Top pair (tT) production

- Squared matrix element structure

|ME|^2 ~ tT^2 +



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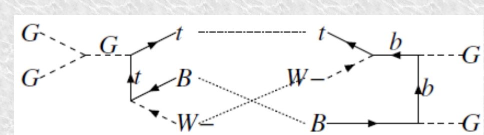
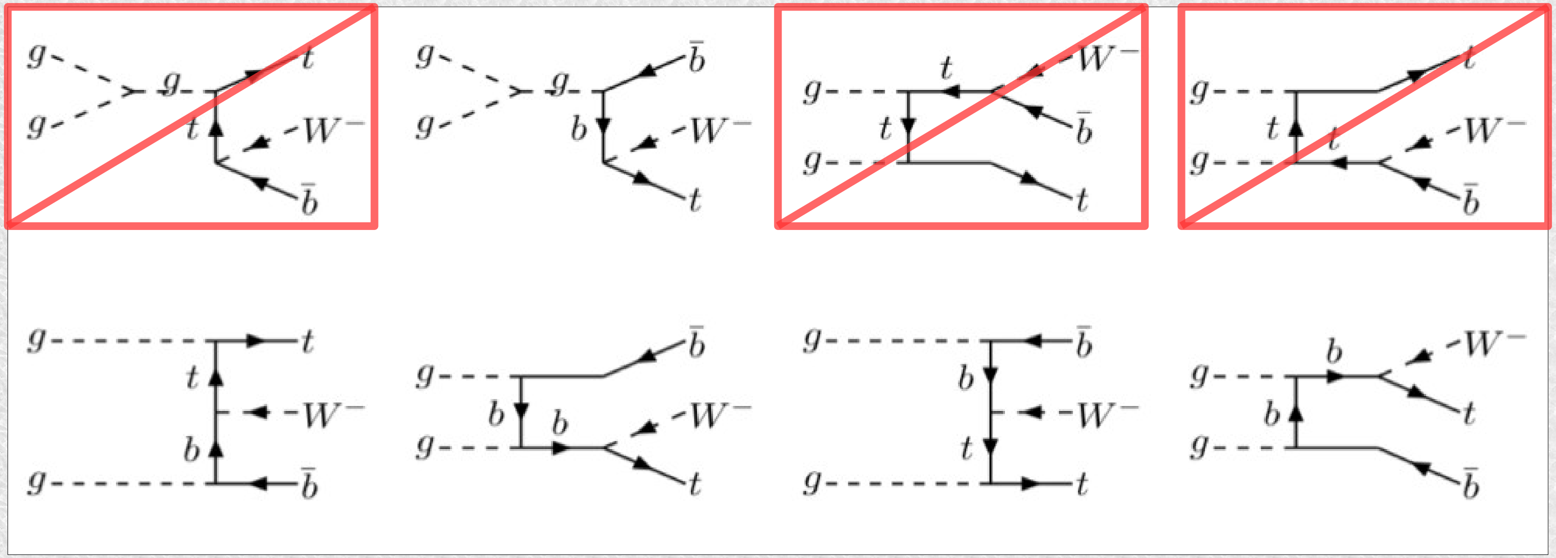


+ tWb^2

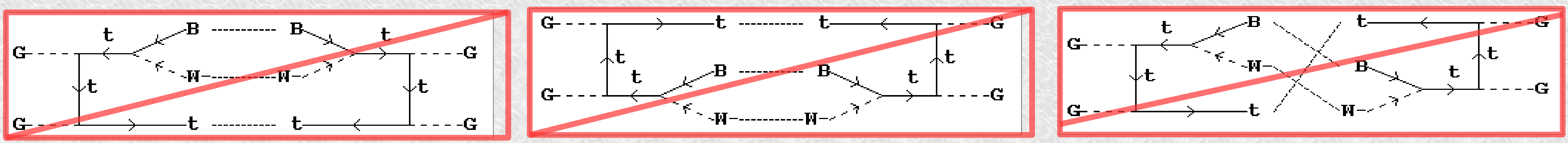
Different schemes for tWb processes highlighting

DR1 (Diagram removal scheme) JHEP0807:029,2008



t t-bar production

DR2 (Diagram subtraction Scheme) Phys. Rev. D 61, 034001



DS1, DS2 schemes EPJC 77, 34 (2017)

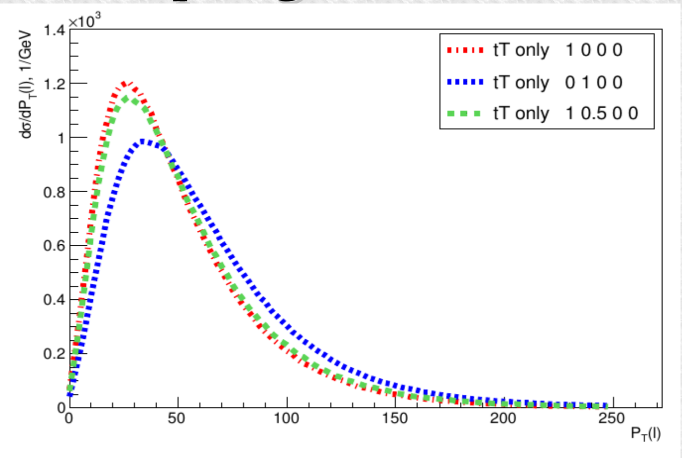
- introduction of the local subtraction term:
    - *cancel the ME from double top production*
    - *gauge invariant*
    - *decreases quickly away from the resonant region*

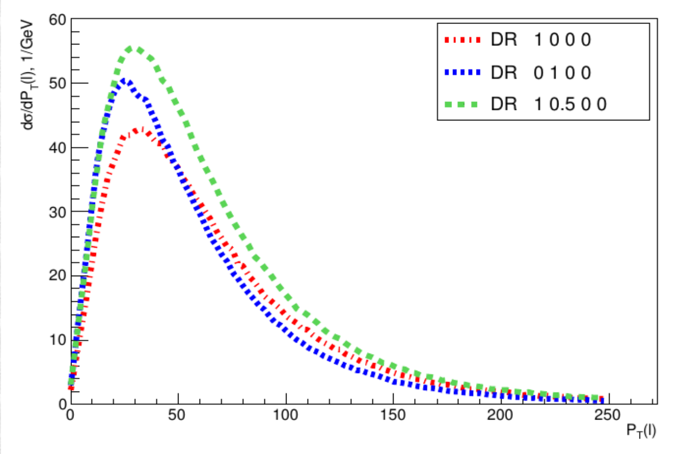
$$|\mathcal{A}_{tWb}|^2_{\mathrm{DS}} = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2 - \mathcal{C}_{2t}$$

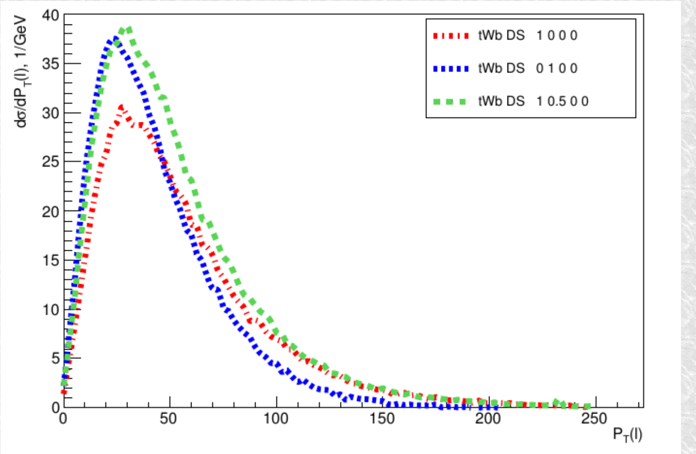
Schemes for tW processes highlighting – the main idea

- What is the most preferable scheme of tW highlighting for the AnomWtb couplings searches?

$$\mathcal{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(f_V^L P_L + f_V^R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}V_{tb}}{M_W}(f_T^L P_L + f_T^R P_R)tW_{\mu}^{-} + h.c.$$

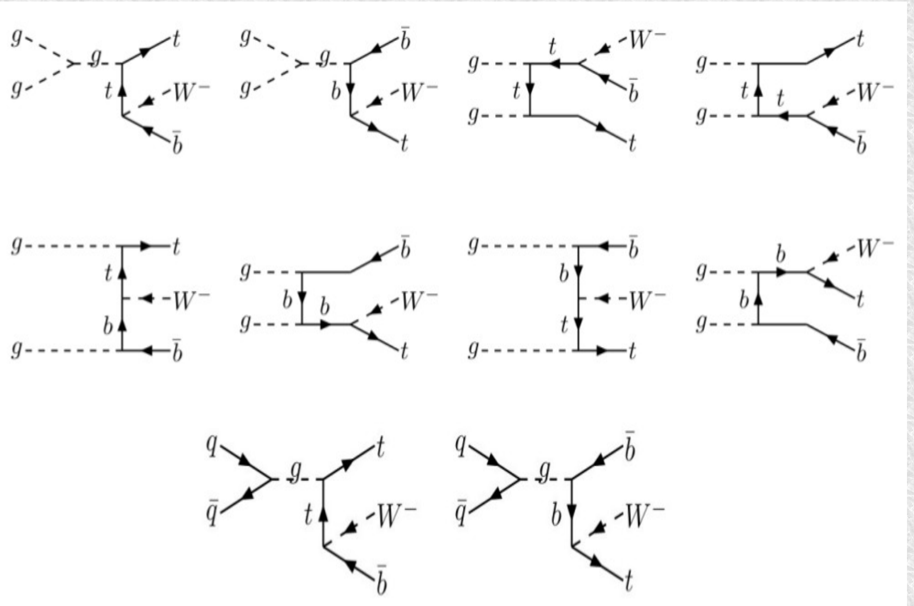






[EPJ Web Conf., 158 (2017) 04004](#)

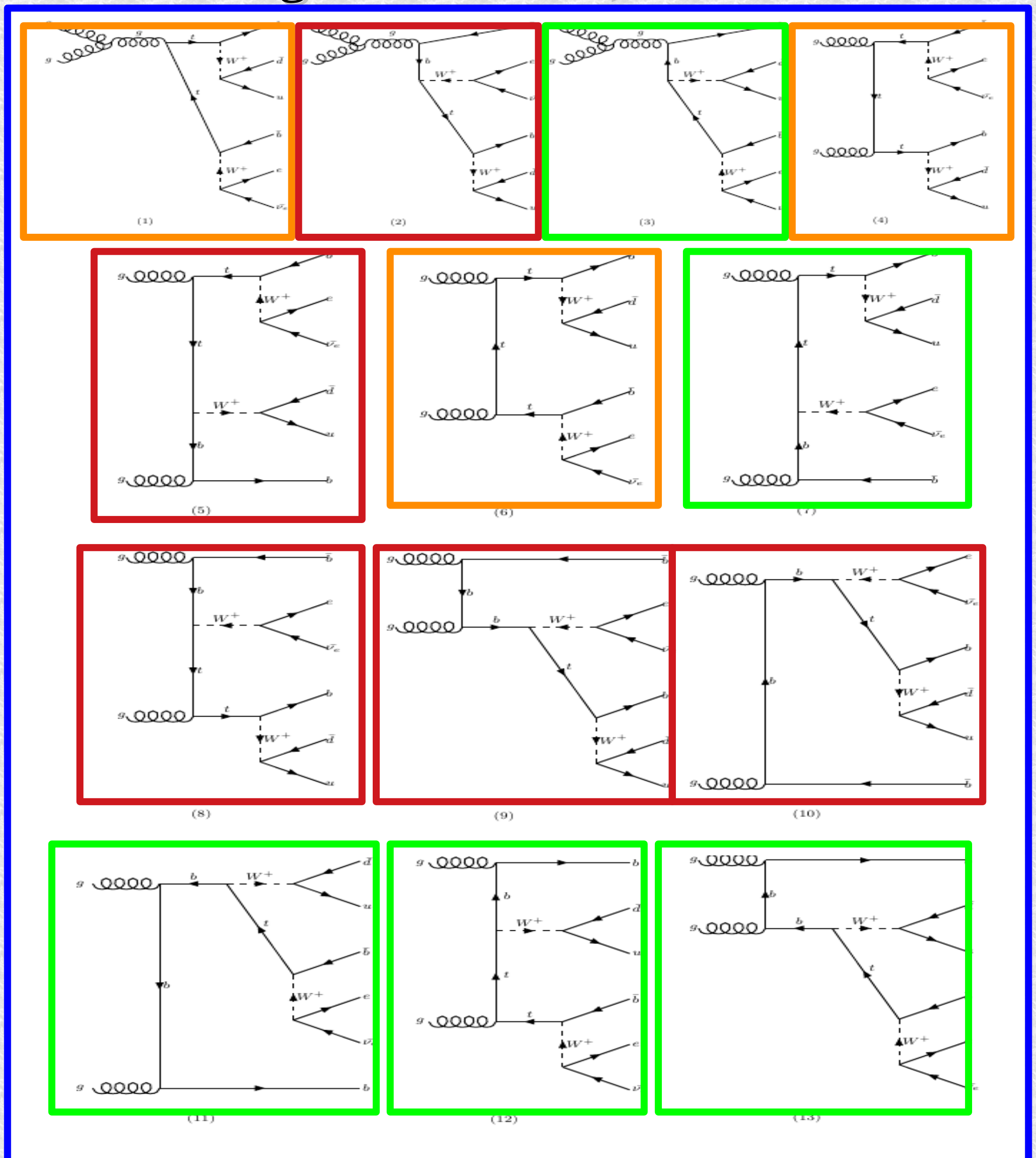
- different schemes of tW highlighting have different sensitivity to the anomalous coupling
- top pair production is also sensitive to the anomalous Wtb couplings
- It's more preferable to use **full gauge-invariant set of diagrams** (without any diagrams removal)



- The IDEA is to separate double and single top resonant contributions to tWb final state using **Neural Networks**

tWb final state: Monte-Carlo simulation

- For DNN training: split sets of events
- Hereafter: a) leading subprocess gg → … b) all decays included
- 13 diagrams in total, 4 sets of events:



Sets of events:

"tT_tW"

"tT"

"tW-B"

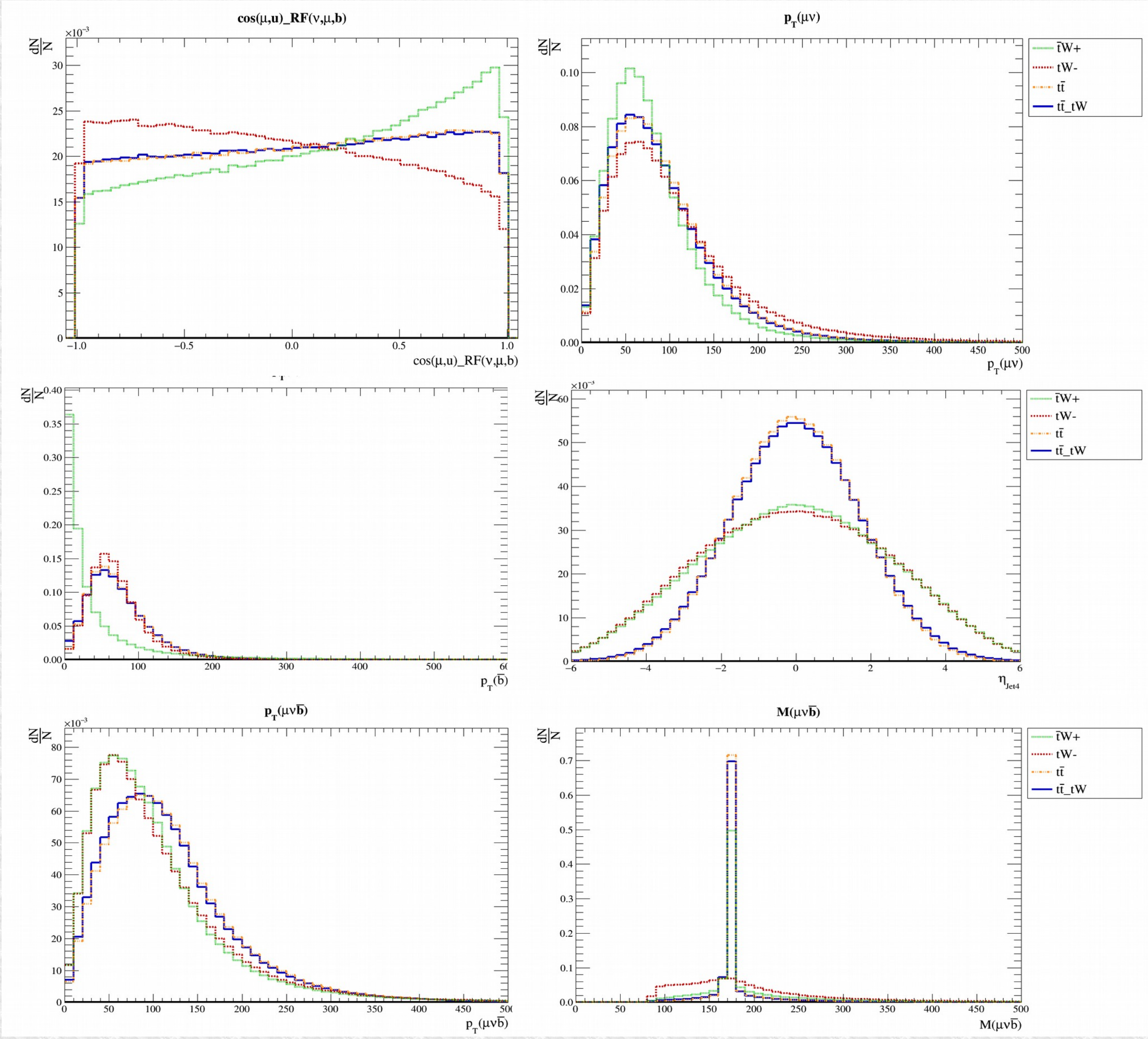
"TW+b"

NN training: kinematic variables

- For DNN training: different kinematic variables with different behaviour for different processes.

- set of main low level variables (for NN to reveal processes regularity)

- set of optimal variables (based on Feynman diagrams analysis)



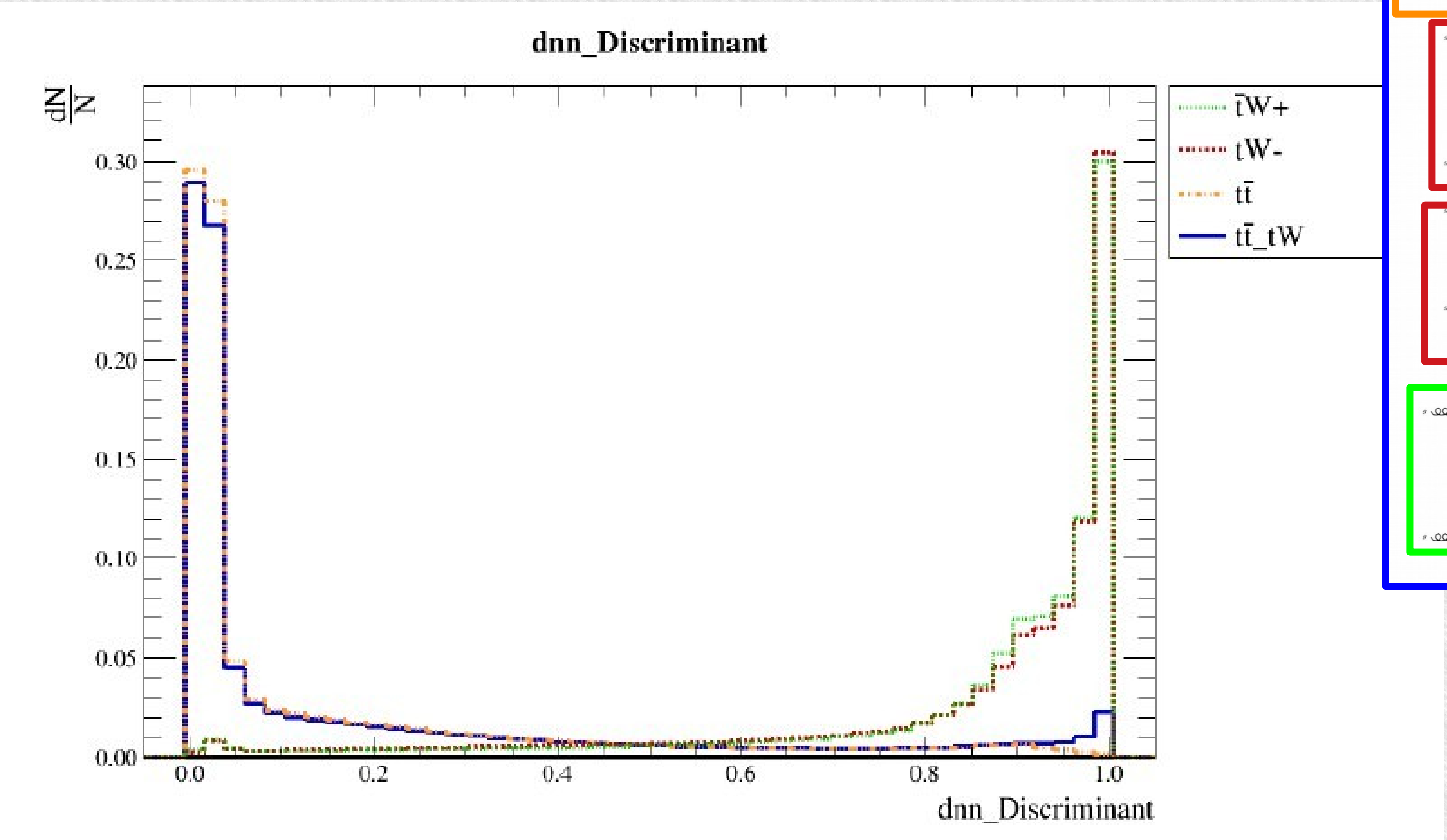
[Physics of Atomic Nuclei 71, 388–393 (2008)]

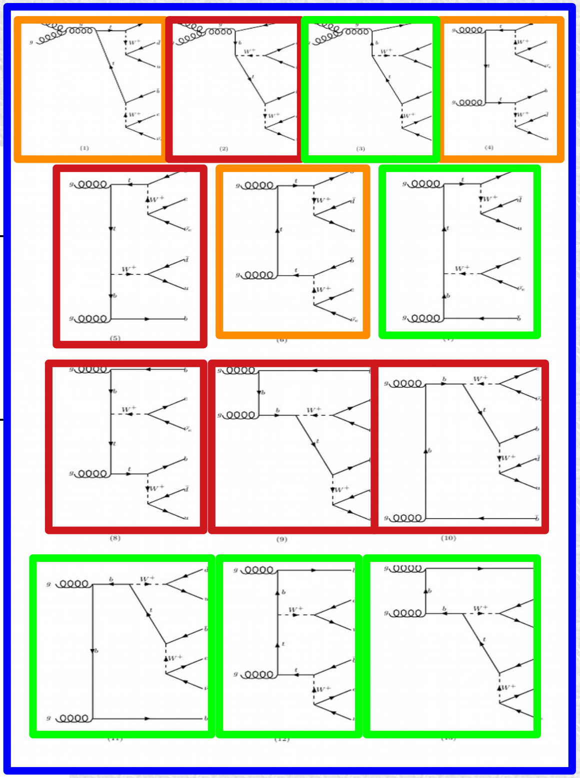
[International Journal of Modern Physics A Vol. 35, No. 21 (2020) 2050119]

[Phys.Lett.B 534 (2002) 97-105]

DNN results: single and double top resonant separation (1)

- DNN classification:
  0: double top resonant processes
  1: single top resonant processes



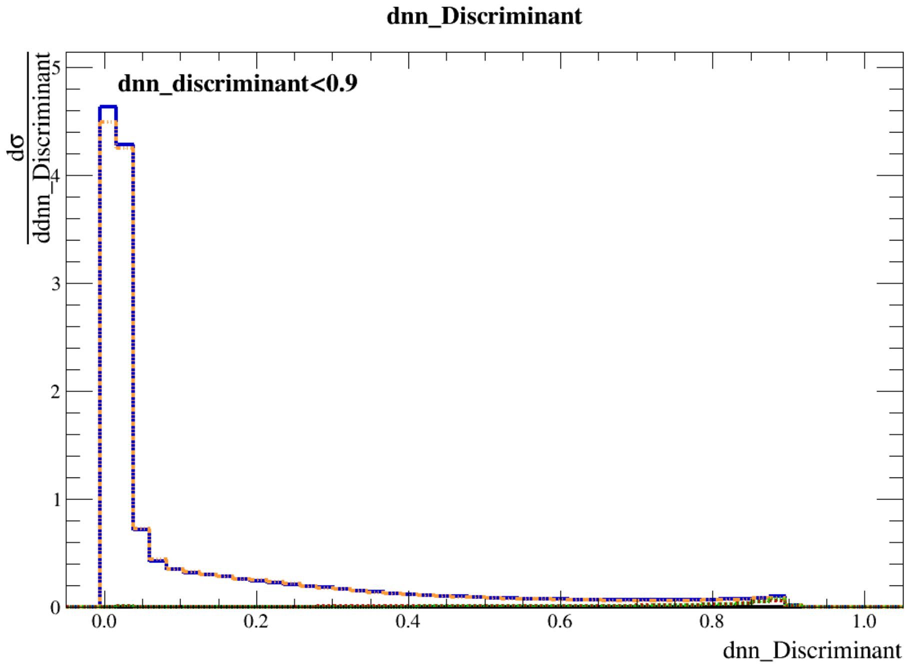


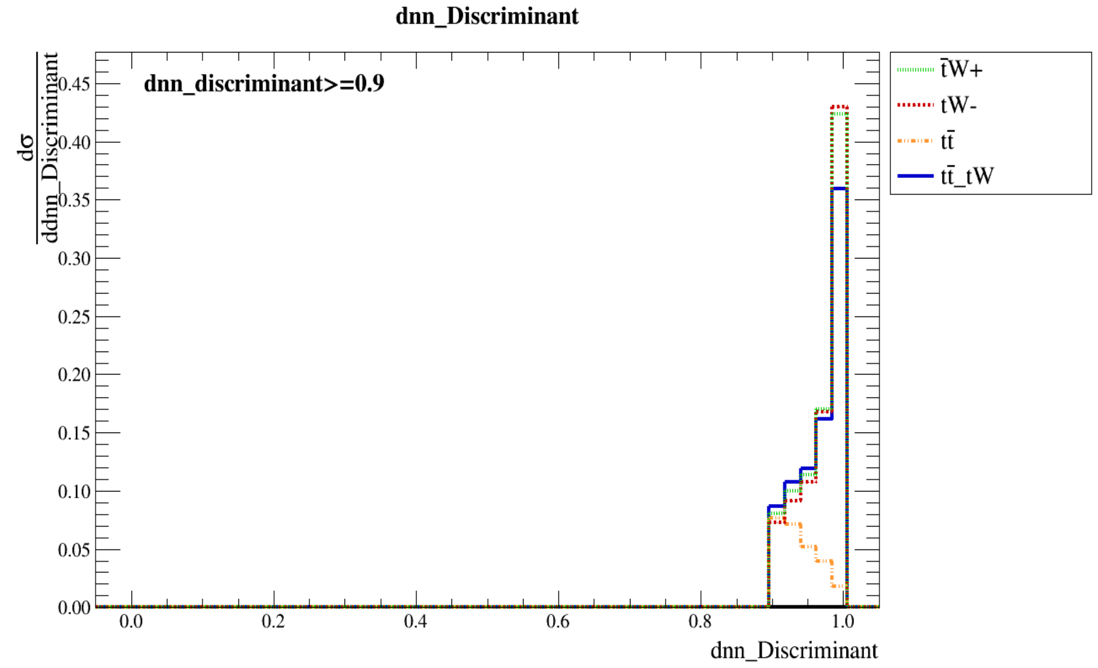
NN separation power

- DNN **successfully separates** double and single resonant contributions to tWb final state
- tT and tW interference "smears" between classified events

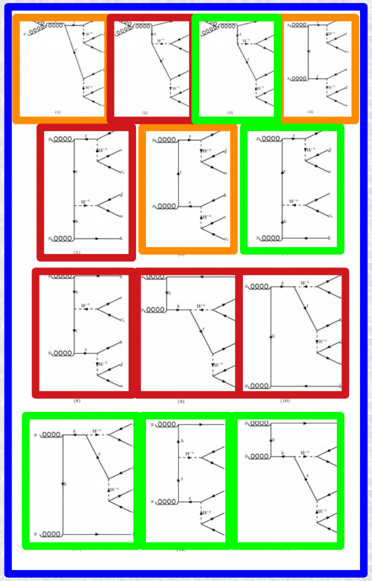
• DNN results: single and double top resonant separation (2)

- **DNN discriminant cut**:
  < 0.9: double resonant contribution   >= 0.9: single resonant contribution





Модель	Сечение, [пб]		Сумма, [пб]
	DNN < 0.9	DNN ≥ 0.9	
“$t\bar{t}$”	14.94	0.26	15.20
“$\bar{t}W+$" DR1	0.26	0.44	0.7
“$tW-$" DR1	0.26	0.44	0.7
“$t\bar{t}$_tW”	15.18	0.84	16.02
интерференция	-0.28 (1.8%)	-0.30 (36%)	-0.6 (3.7%)



EFT and Anomalous Couplings approach

- **Effective Field Theory** approach:

$$\mathcal{L}_{eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2} O_i$$

Nucl.Phys.B 268 (1986) 621-653

Z. Phys. C31 (1986) 433-437

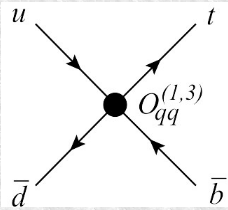
- operators that contribute to the Wtb vertex:

$$O^{(3,3+3)}_{\varphi q} = \frac{i}{2}\left[\varphi^\dagger(\tau^I D_\mu - \overleftarrow{D}_\mu \tau^I)\varphi\right](\bar{q}_{L3}\gamma^\mu \tau^I q_{L3}), \qquad O^{33}_{\varphi\varphi} = i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{t}_R \gamma^\mu b_R),$$

$$O^{33}_{dW} = (\bar{q}_{L3}\sigma^{\mu\nu}\tau^I b_R)\varphi W^I_{\mu\nu}, \qquad O^{33}_{uW} = (\bar{q}_{L3}\sigma^{\mu\nu}\tau^I t_R)\tilde{\varphi} W^I_{\mu\nu},$$

$$O^{(1,3)}_{qq} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{q}\gamma^\mu \tau^I q)$$

contact four-fermion interactions (not a part of the Wtb vertex):



- **Anomalous Couplings** approach:

Phys.Rev.D83:034006,2011

$$\mathcal{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^\mu V_{tb}(f_V^L P_L + f_V^R P_R) t W^-_\mu$$
$$- \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu} q_\nu V_{tb}}{M_W}(f_T^L P_L + f_T^R P_R) t W^-_\mu + h.c.$$

order:

$1/\Lambda^2$	$1/\Lambda^4$
f_V^L	$(f_V^L)^2$
...	$(f_V^R)^2$
...	$(f_T^L)^2$
f_T^R	$(f_T^R)^2$

- Translation:

$$|f_V^L| = 1 + |C_{\phi q}|\frac{v^2}{V_{tb}\Lambda^2} \qquad |f_V^R| = \frac{1}{2}|C_{\phi\phi}|\frac{v^2}{V_{tb}\Lambda^2}$$

$$|f_T^L| = \sqrt{2}|C_{bW}|\frac{v^2}{V_{tb}\Lambda^2} \qquad |f_T^R| = \sqrt{2}|C_{tW}|\frac{v^2}{V_{tb}\Lambda^2}$$

Nucl.Phys.B 812 (2009) 181-204

PoS ICHEP2010:378,2010

AnomWtb: CMS analysis

- «Search for new physics in top quark production in dilepton final states in proton-proton collisions at$\sqrt{s}$= 13 TeV»

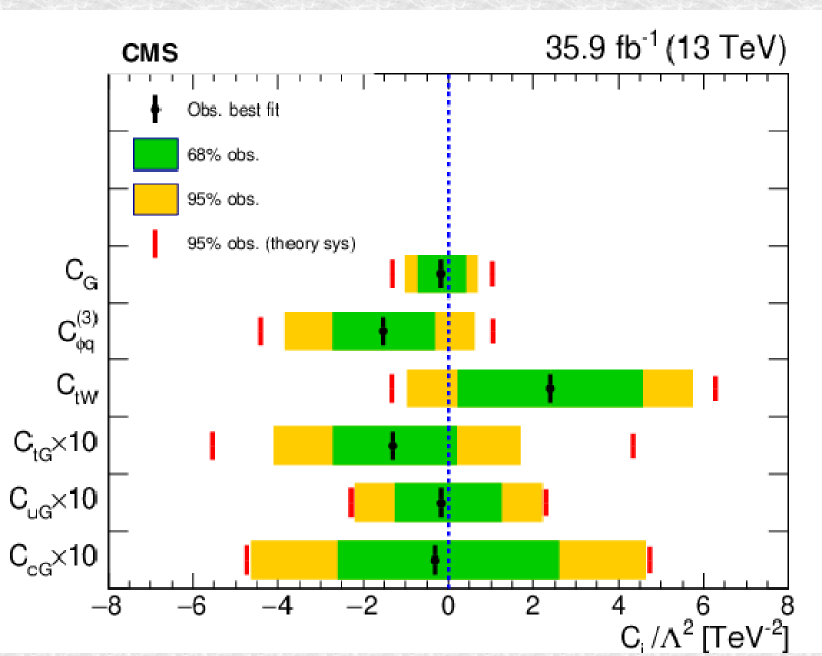
  - dilepton final state

  - EFT effects in the top quark production, not in the decay

  - the rates of tW and tT production are used to probe the $C^{(3)}_{\phi q}, C_{tW}, C_{tG}, C_G$

  - variations in both rate and kinematic distributions: C_{uG}, C_{cG}

[Eur. Phys. J. C 79 (2019) 886]



Effective coupling	Channel	Observed [TeV^{-2}] Best fit	[68% CI]	[95% CI]	Expected [TeV^{-2}] Best fit	[68% CI]	[95% CI]
C_G/Λ^2	ee	−0.14	[−0.82, 0.51]	[−1.14, 0.83]	0.00	[−0.90, 0.59]	[−1.20, 0.88]
	eμ	−0.18	[−0.73, 0.42]	[−1.01, 0.70]	0.00	[−0.82, 0.51]	[−1.08, 0.77]
	$\mu\mu$	−0.14	[−0.75, 0.44]	[−1.06, 0.75]	0.00	[−0.88, 0.57]	[−1.16, 0.85]
	Combined	−0.18	[−0.73, 0.42]	[−1.01, 0.70]	0.00	[−0.82, 0.51]	[−1.07, 0.76]
$C^{(3)}_{\phi q}/\Lambda^2$	ee	1.12	[−1.18, 2.89]	[−4.03, 4.37]	0.00	[−2.53, 1.74]	[−6.40, 3.27]
	eμ	−0.70	[−2.16, 0.59]	[−3.74, 1.61]	0.00	[−1.34, 1.12]	[−2.57, 2.15]
	$\mu\mu$	1.13	[−0.87, 2.86]	[−3.58, 4.46]	0.00	[−2.20, 1.92]	[−4.68, 3.66]
	Combined	−1.52	[−2.71, −0.33]	[−3.82, 0.63]	0.00	[−1.05, 0.88]	[−2.04, 1.63]
C_{tW}/Λ^2	ee	6.18	[−3.02, 7.81]	[−4.16, 8.95]	0.00	[−2.02, 6.81]	[−3.33, 8.12]
	eμ	1.64	[−0.80, 5.59]	[−1.89, 6.68]	0.00	[−1.40, 6.19]	[−2.39, 7.18]
	$\mu\mu$	−1.40	[−3.00, 7.79]	[−4.23, 9.01]	0.00	[−2.18, 6.97]	[−3.63, 8.42]
	Combined	2.38	[0.22, 4.57]	[−0.96, 5.74]	0.00	[−1.14, 5.93]	[−1.91, 6.70]
C_{tG}/Λ^2	ee	−0.19	[−0.40, 0.02]	[−0.65, 0.22]	0.00	[−0.22, 0.21]	[−0.44, 0.41]
	eμ	−0.03	[−0.19, 0.11]	[−0.34, 0.27]	0.00	[−0.17, 0.15]	[−0.34, 0.29]
	$\mu\mu$	−0.15	[−0.34, 0.02]	[−0.53, 0.19]	0.00	[−0.19, 0.18]	[−0.40, 0.35]
	Combined	−0.13	[−0.27, 0.02]	[−0.41, 0.17]	0.00	[−0.15, 0.14]	[−0.30, 0.28]
C_{uG}/Λ^2	ee	−0.017	[−0.22, 0.22]	[−0.37, 0.37]	0.00	[−0.29, 0.29]	[−0.42, 0.42]
	eμ	−0.017	[−0.17, 0.17]	[−0.29, 0.29]	0.00	[−0.26, 0.26]	[−0.38, 0.38]
	$\mu\mu$	−0.017	[−0.17, 0.17]	[−0.29, 0.29]	0.00	[−0.27, 0.27]	[−0.38, 0.38]
	Combined	−0.017	[−0.13, 0.13]	[−0.22, 0.22]	0.00	[−0.21, 0.21]	[−0.30, 0.30]
C_{cG}/Λ^2	ee	−0.032	[−0.47, 0.47]	[−0.78, 0.78]	0.00	[−0.63, 0.63]	[−0.92, 0.92]
	eμ	−0.032	[−0.34, 0.34]	[−0.60, 0.60]	0.00	[−0.56, 0.56]	[−0.81, 0.81]
	$\mu\mu$	−0.032	[−0.36, 0.36]	[−0.63, 0.63]	0.00	[−0.58, 0.58]	[−0.84, 0.84]
	Combined	−0.032	[−0.26, 0.26]	[−0.46, 0.46]	0.00	[−0.46, 0.46]	[−0.65, 0.65]

AnomWtb couplings in tWb process

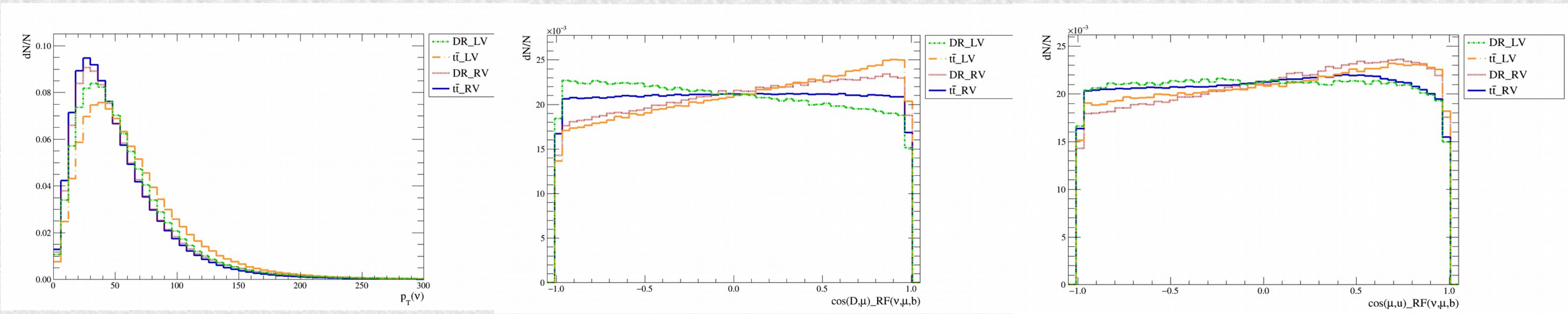
- As a start: (LV, RV) scenario:

$$\mathcal{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(f_V^L P_L + f_V^R P_R)tW_{\mu}^{-}$$

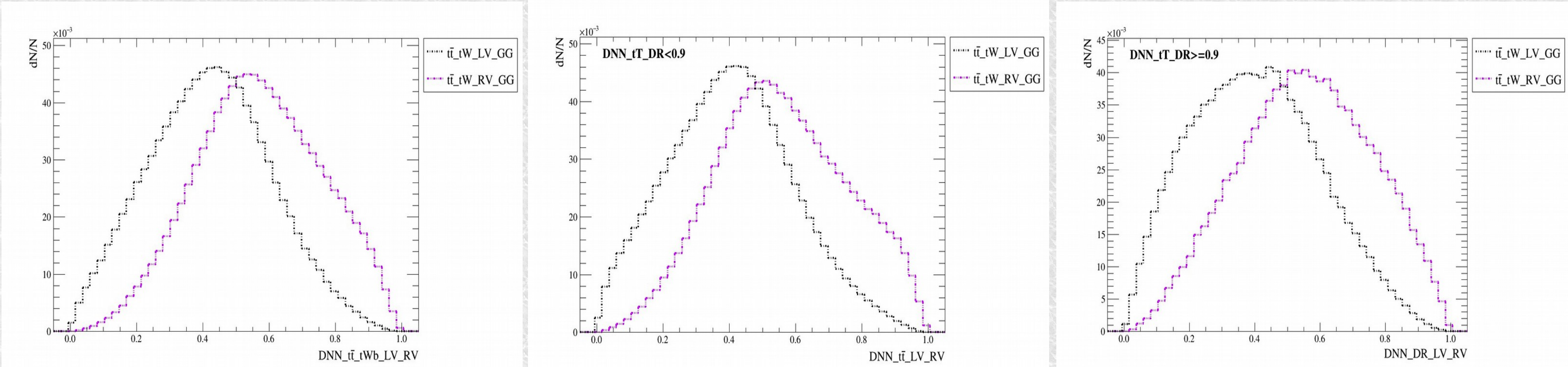
- Different sets of MC events for one and double resonant top production

$$LV\,(f_V^L=1, f_V^R=0) \quad RV\,(f_V^L=0, f_V^R=1)$$

- Kinematic variables as the ones for DNN training:

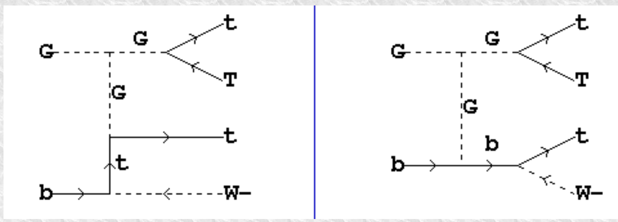


- Preliminary results for LV/RV scenario separation by DNN



Triple and Quadrupole top quark production

- Processes of three top quarks production in association with W-boson (*CS = 1.9 fb*) :



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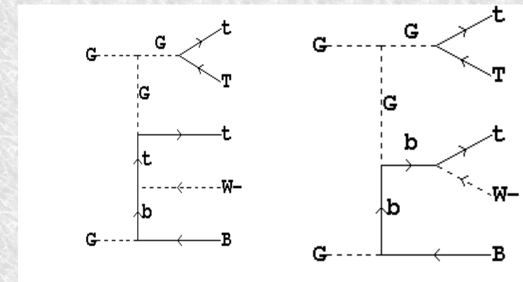
- NLO process:



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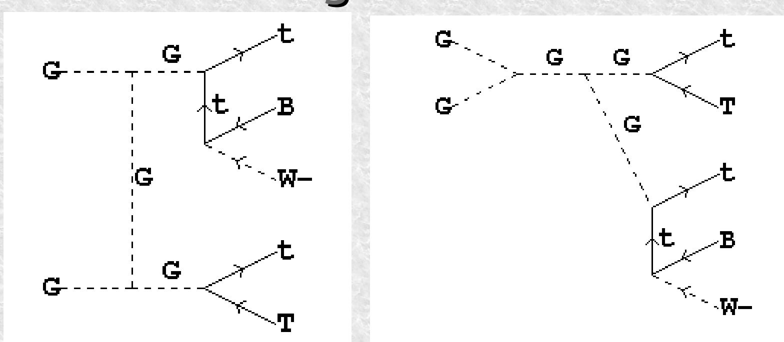
[Triple top quark production in Standard Model](#)

- Overlapping with four top quark production process (*CS = 17 fb*) with the same final signature:



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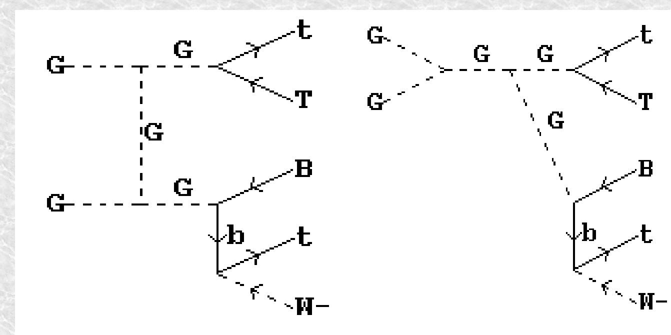

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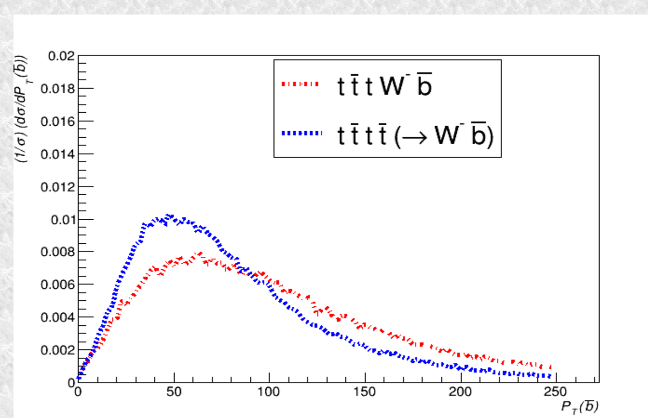
- LHC searches for 4 top quarks production: [Eur. Phys. J. C 80 (2020) 75](#)

- Set of variables that can be used for DNN training for separation between triple and quadrupole top quark



Conclusion

- Neural Network method to separate double and single resonant top production contributions to tWb final state is presented
- DNN successfully separates double and single top quark contributions to tWb final state
- Different regions of phase space with double and single resonant contribution separated by NN can be further used for Anomalous Wtb operators contribution to Wtb vertex searches analysis
- Preliminary results for LV and RV separation by DNN are presented
- The same strategy is applying to separate triple and quadrupole resonant top production contribution to tttWb final state
- Published results:

Moscow University Physics Bulletin, Allerton Press (New York, N.Y., US), 78, № 6, 707-715

Вестник Московского университета. Серия 3: Физика, астрономия, Изд-во Моск. ун-та (М.), 78, № 6, 2360201

- The work is supported by the RSF grant № 22-12-00152