Separation between top pair and Single Top contributions with tWb final state using Neural Networks

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

Lomonosov Moscow State University (SINP MSU)

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A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute)
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Top quark as is

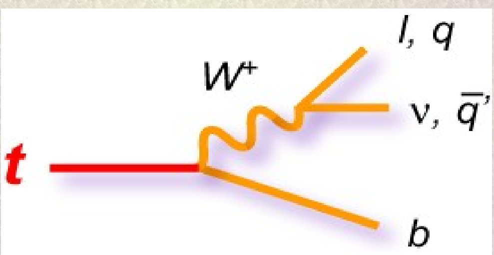
three
quarks
generation

u	**c**	**t**
d	**s**	**b**

(V-A) interaction vertex

$$\Gamma_{tqW} = -\frac{g}{\sqrt{2}} V_{tq}\, \bar{q}\, \gamma_{\mu} \frac{1}{2}(1-\gamma_5) W^{\mu} t$$

Decay mode
(~100%):



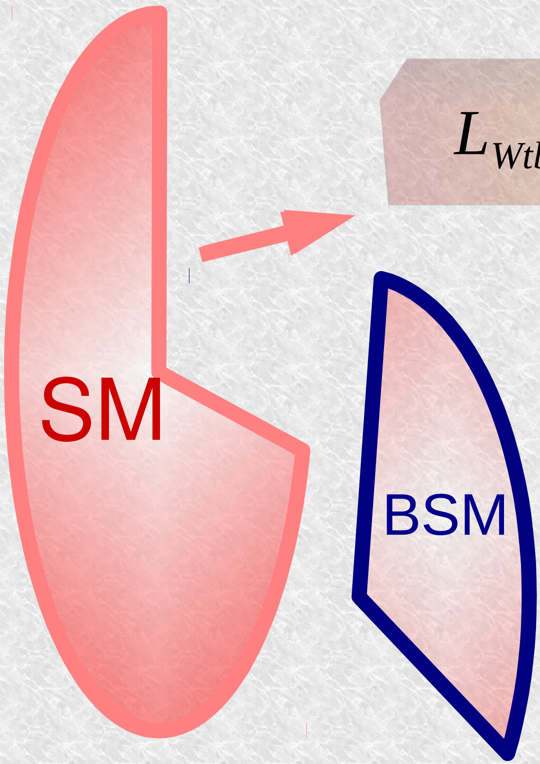
t-quark
in SM

$$M_{top} = 172.69\ \mathrm{GeV}$$
(PDG)

...top quark is a good candidate
for testing the SM

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

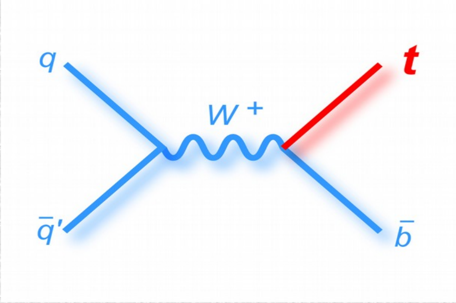
→ W'

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

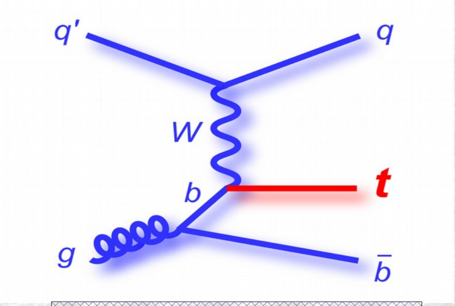
→ Anomalous Wtb couplings

→ FCNC

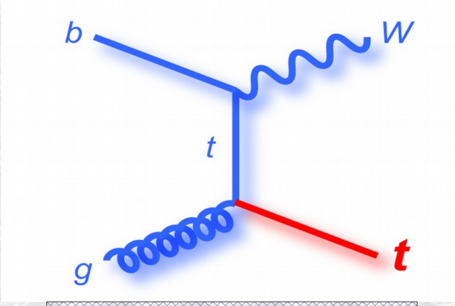
Single top quark production processes



s-channel



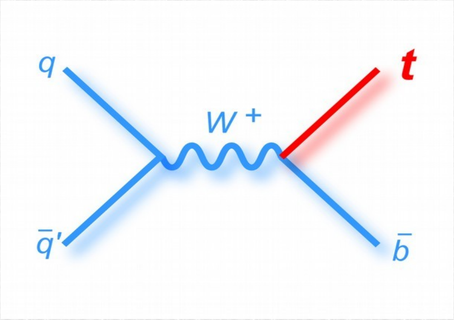
t-channel

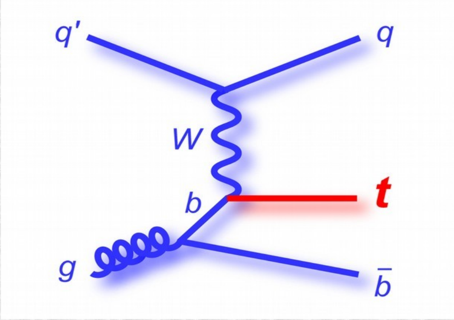


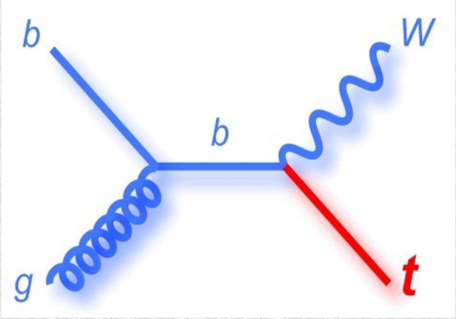
tW-channel

Single Top quark producton 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 ATLAS t-channel observation
tW production	0.28	22.37	71.7	84.4	CMS Observation @8TeV ATLAS and CMS combination







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

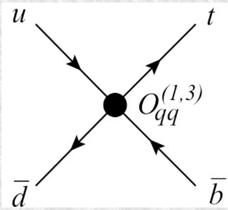
- operators that contribute to the Wtb vertex:

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

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

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

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



- **Anomalous Couplings** approach:

Phys.Rev.D83:034006,2011

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

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:

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

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

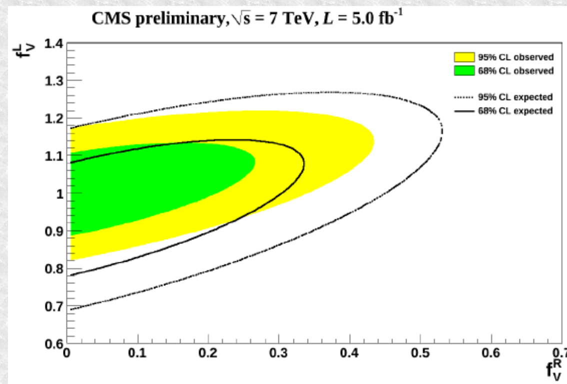
Nucl.Phys.B 812 (2009) 181-204

PoS ICHEP2010:378,2010

AnomWtb couplings search at CMS

- CMS Single Top group used this approach for the experimental searches for the Anomalous contribution to the Wtb vertex arXiv:1610.03545
- Results: 2D and 1D limits on the Anomalous Wtb couplings for 3 scenarios: (Lv,Rv), (Lv,Lt), (Lv, Rt)

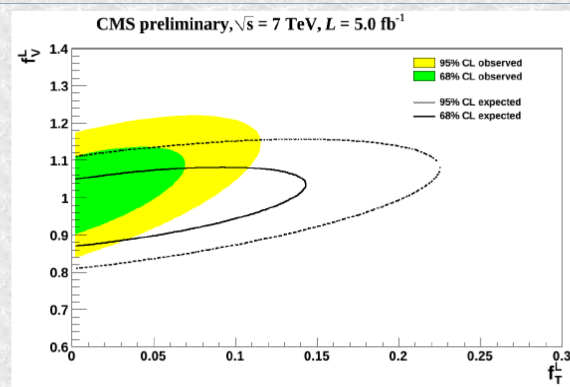
$(L_V\ R_V)$



$|L_V| > 0.97\ (0.92)$

$|R_V| < 0.28\ (0.31)$

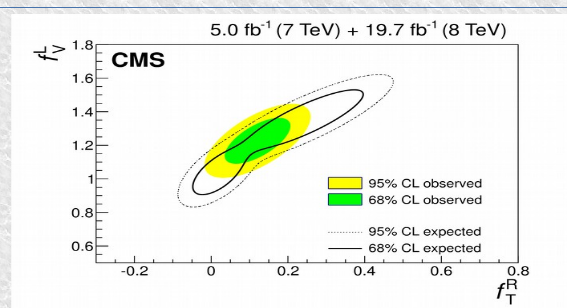
$(L_V\ L_T)$



$|L_V| > 0.92\ (0.92)$

$|L_T| < 0.10\ (0.14)$

$(L_V\ R_T)$



$|L_V| > 0.94\ (0.93)$

$-0.046\ (-0.050) < |R_T| < 0.046\ (0.041)$

AnomWtb: CMS analysis

- «Search for new physics in top quark production in dilepton final states in proton-proton collisions at√s= 13 TeV»

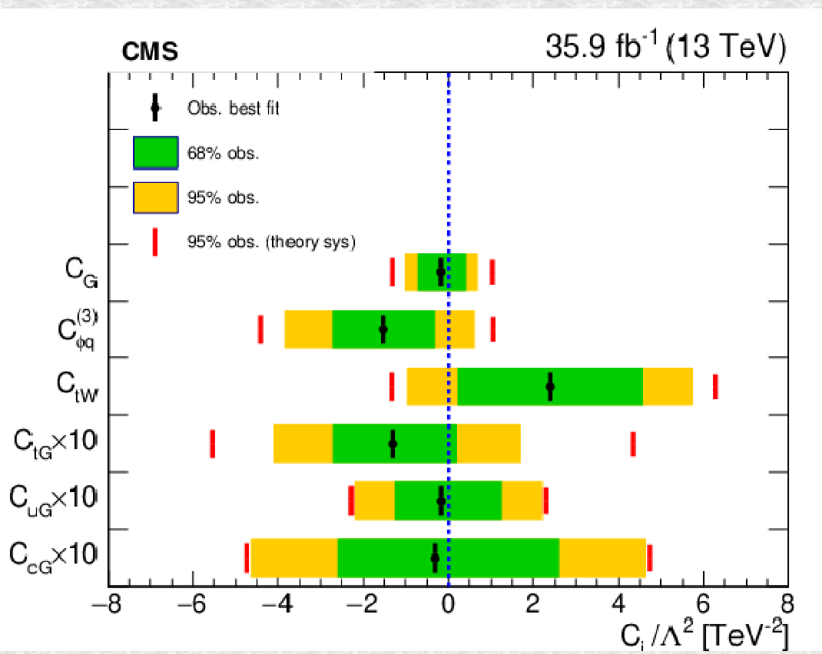
  - dilepton final state

  - 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}

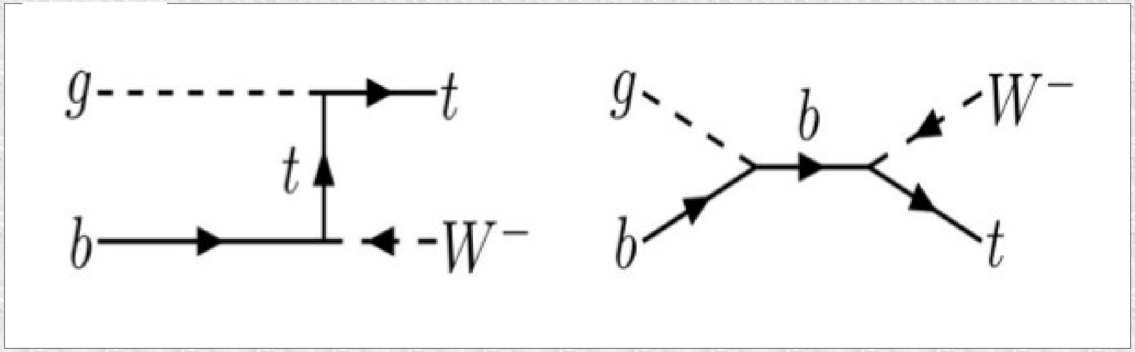
Eur. Phys. J. C 79 (2019) 886



Effective coupling	Channel	Observed [TeV^{-2}] Best fit	Observed [68% CI]	Observed [95% CI]	Expected [TeV^{-2}] Best fit	Expected [68% CI]	Expected [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]

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**

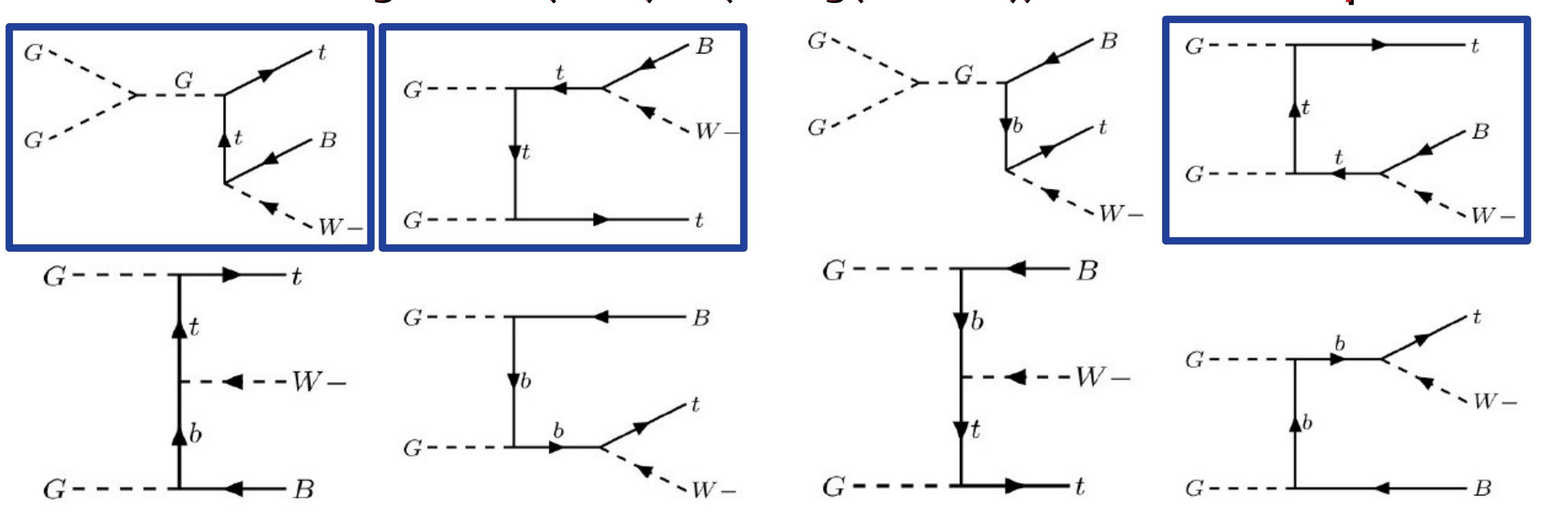
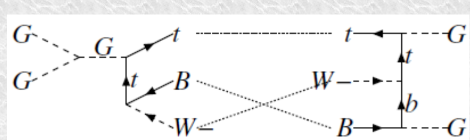
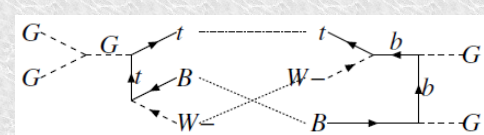


Figure 1: Diagrams for the process $gg \to t\bar{b}W^-$.

Top pair (tT) production

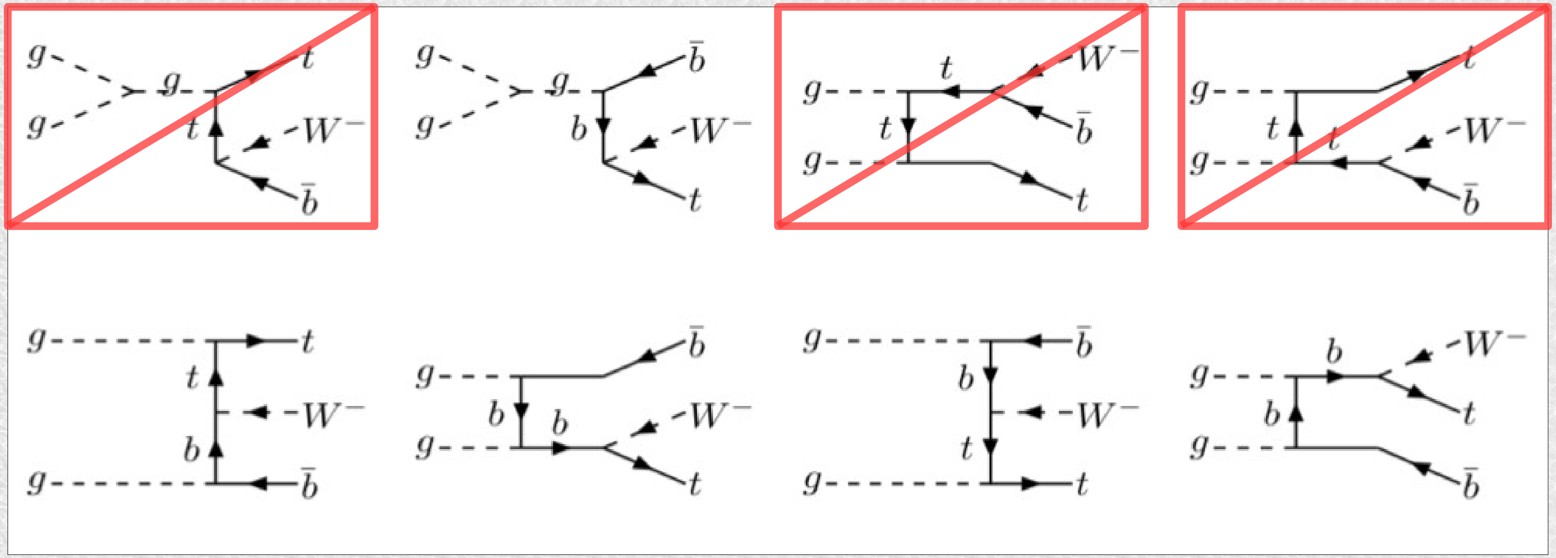
- Squared matrix element structure

|ME|^2 ~ tT^2 +  ...  + tWb^2

[ATLAS CS measurements]

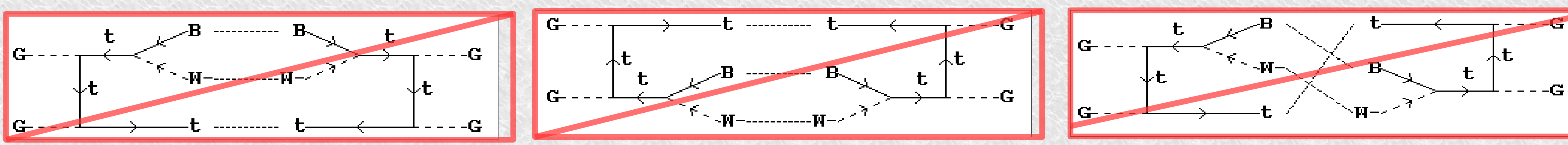
Different schemes for tWb processes highlighting

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)

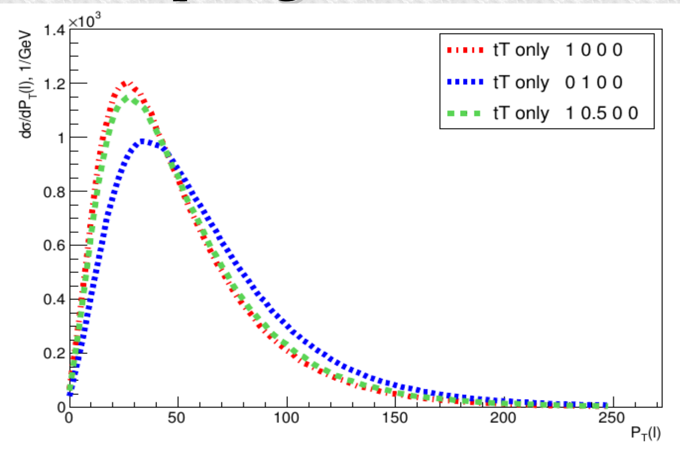
- introduction of the local subtraction term:
  - *cancel the ME from double top production*
  - *gauge invariant*
  - *decreases quickly away from the resonant region*

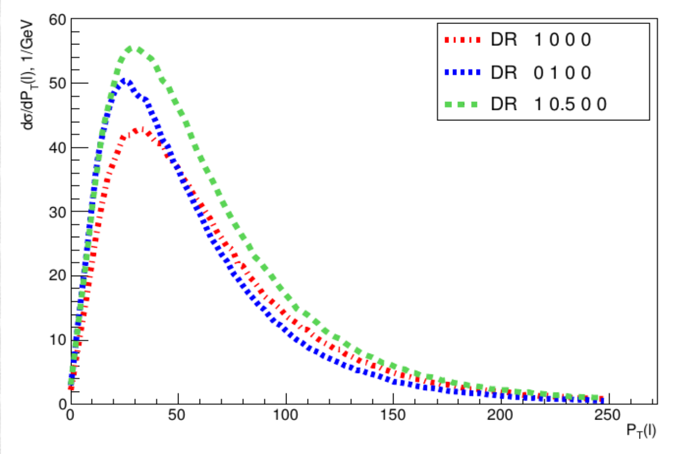
$$|\mathcal{A}_{tWb}|^2_{\mathrm{DS}} = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2 - \mathcal{C}_{2t}$$

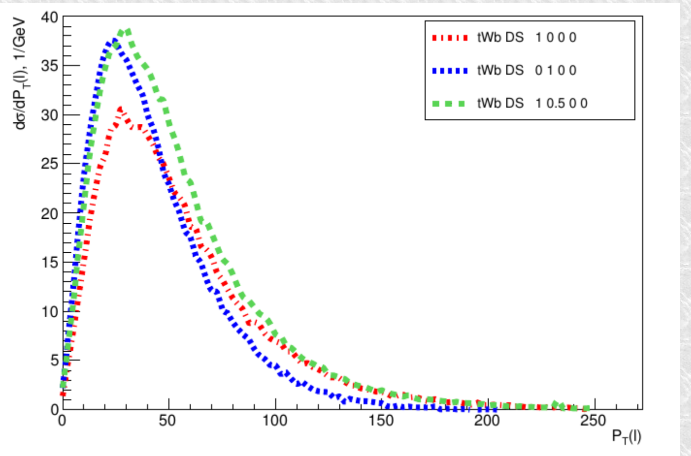
Schemes for tW processes highlighting (2)

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

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

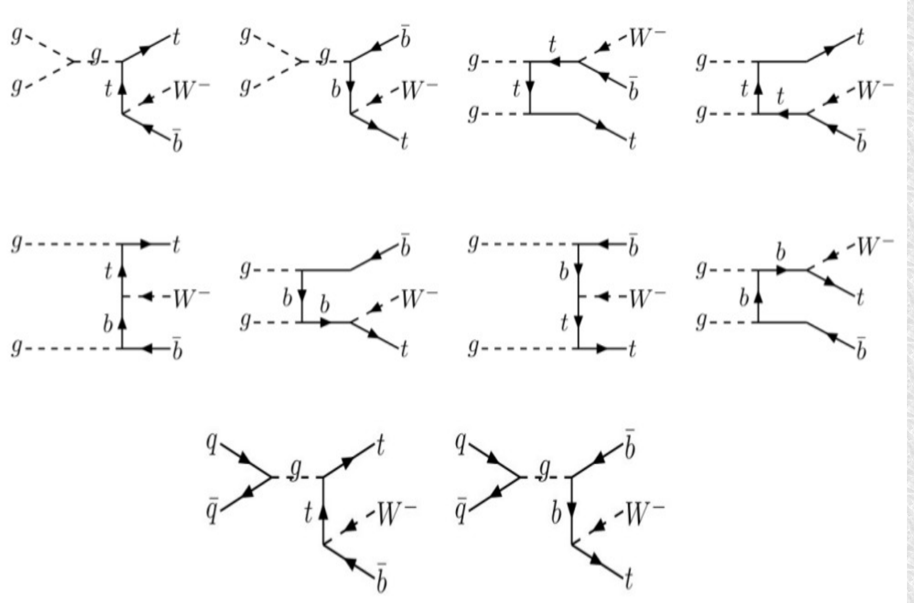






EPJ Web Conf., 158 (2017) 04004

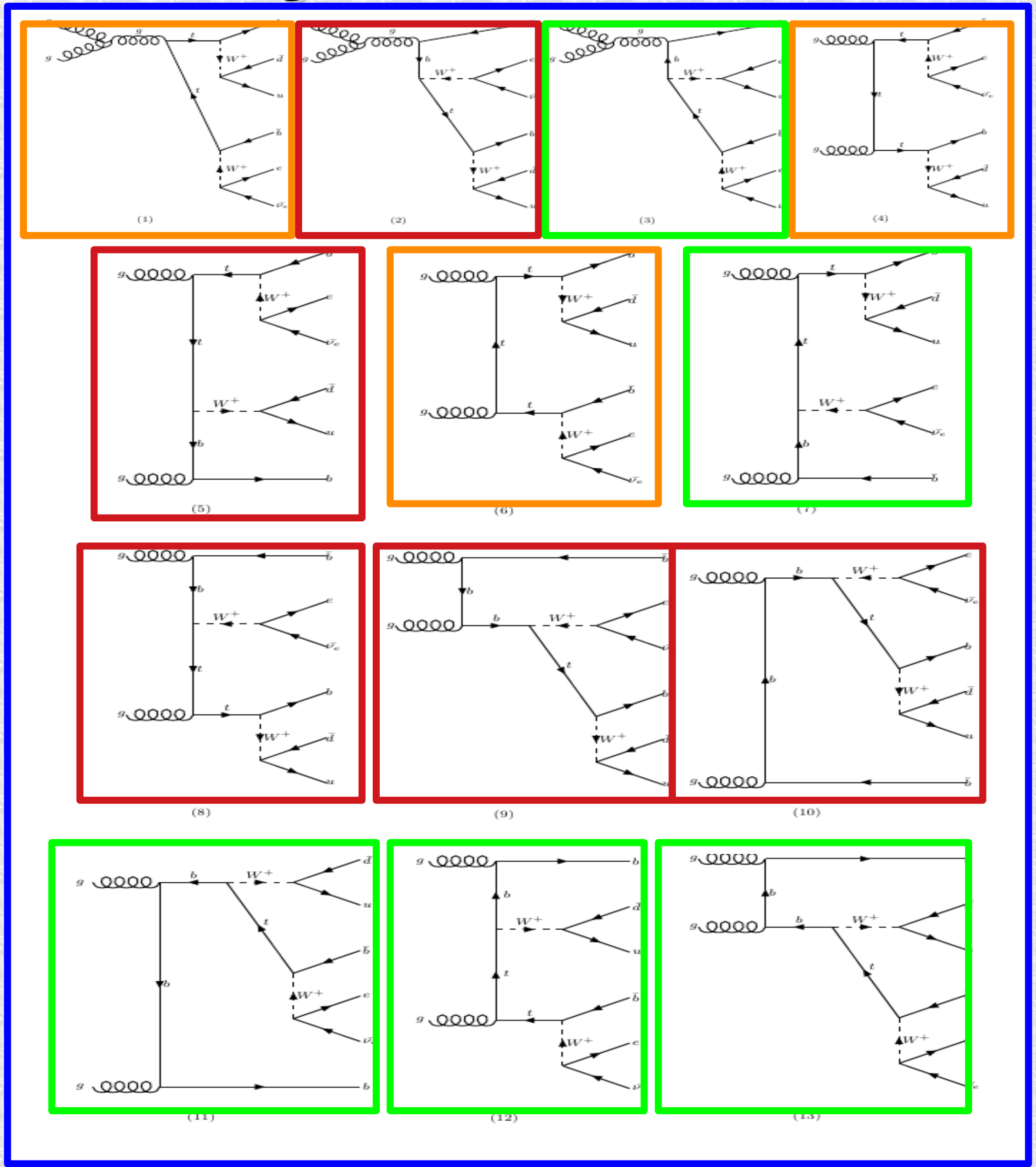
- different schemes of tW highlighting have different sensitivity to the anomalous coupling
- top pair production is also sensitive to the anomalous Wtb couplings
- It's more preferable to use **full gauge-invariant set of diagrams** (without any diagrams removal)



- 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: separate sets of events
- Hereafter: a) leading subprocess gg → … b) all decays iincluded
- 13 diagrams in total, 4 sets of events:



Sets of events:

“tT_tW”

“tT”

“tW-B”

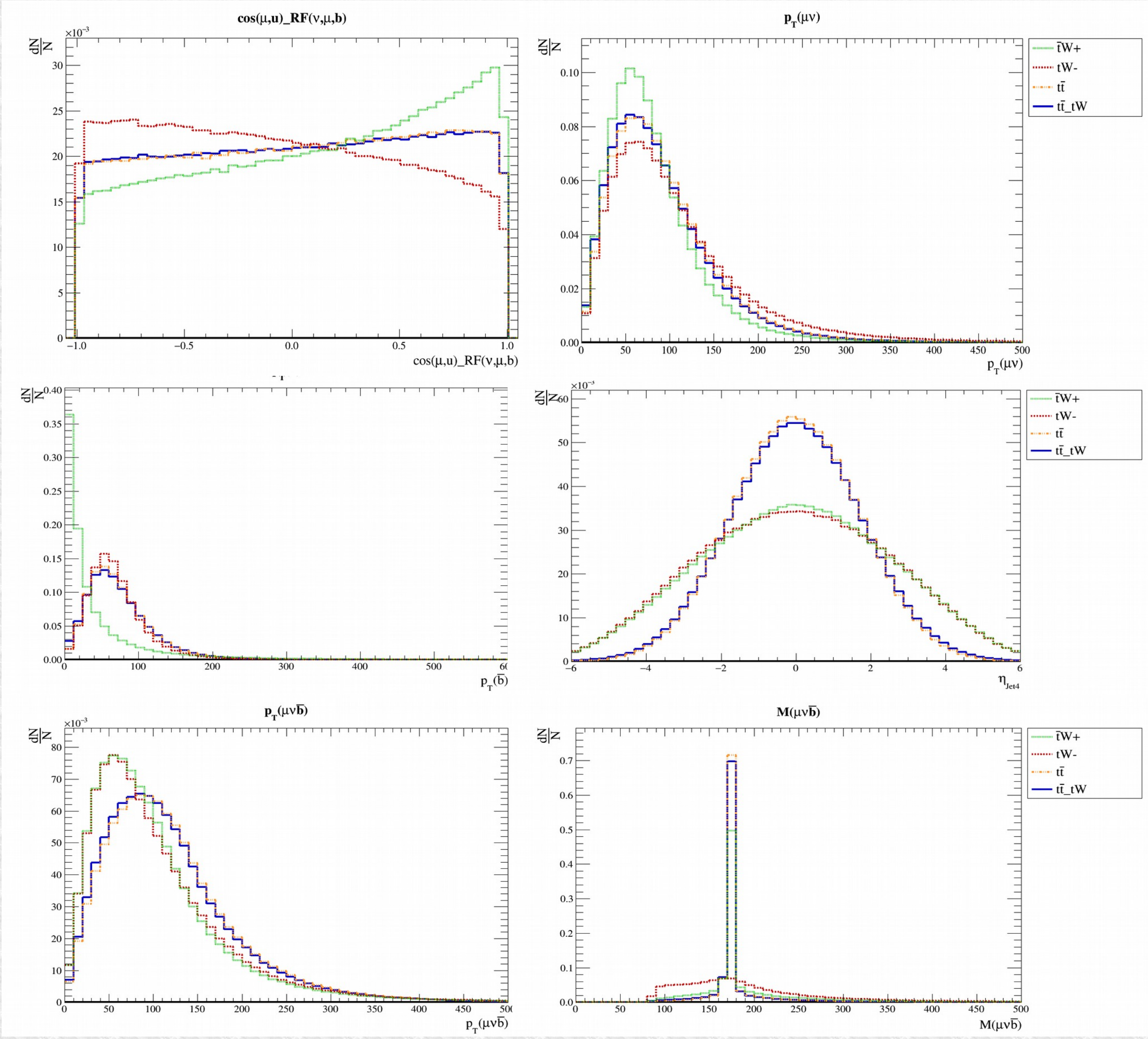
“TW+b”

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)



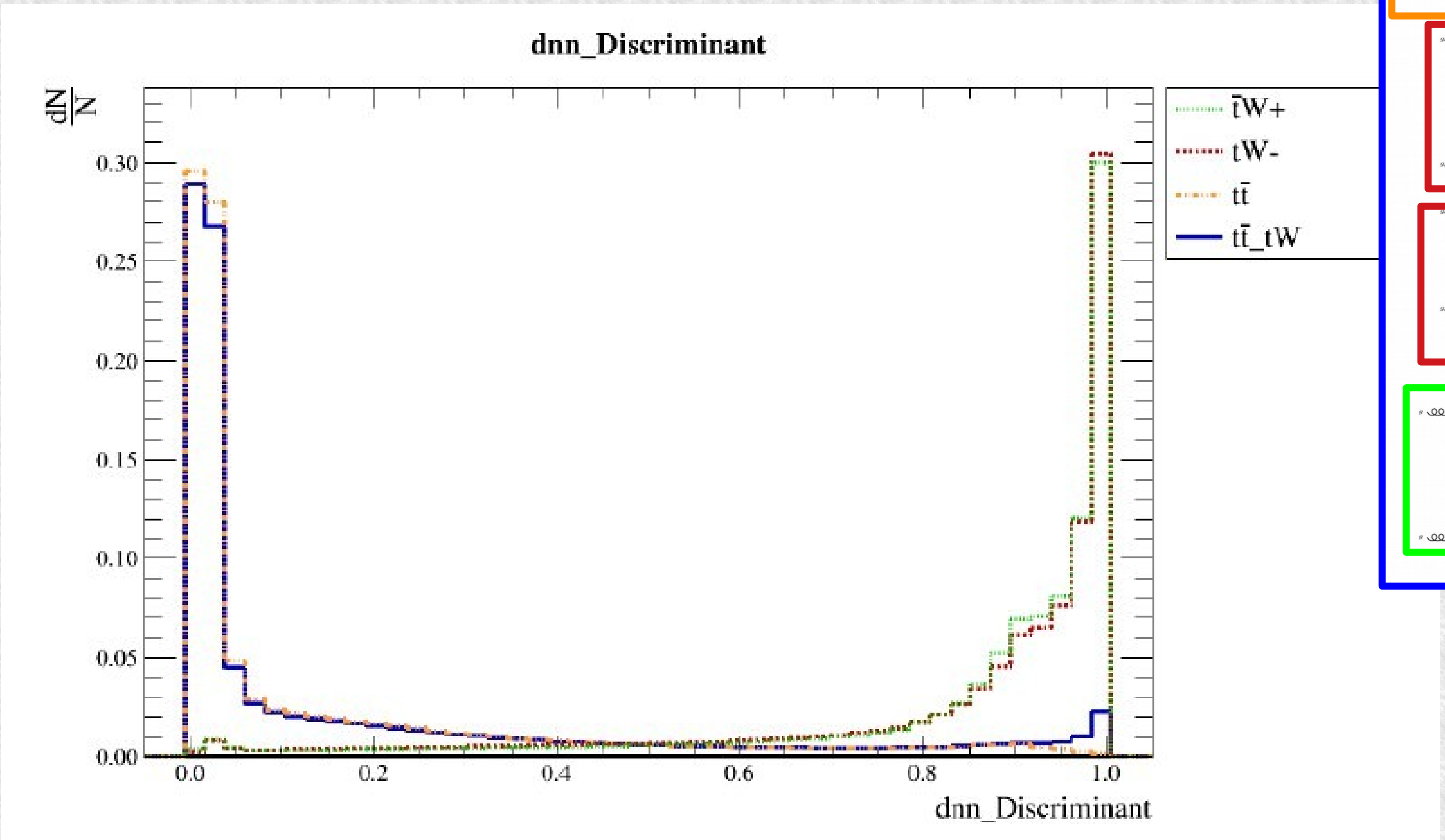
[Physics of Atomic Nuclei 71, 388–393 (2008)]

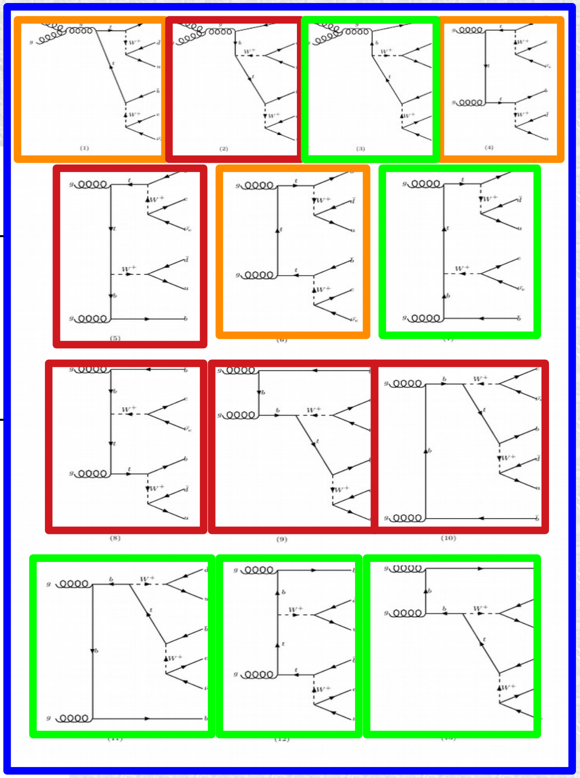
[International Journal of Modern Physics A Vol. 35, No. 21 (2020) 2050119]

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

DNN results: separation (1)

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



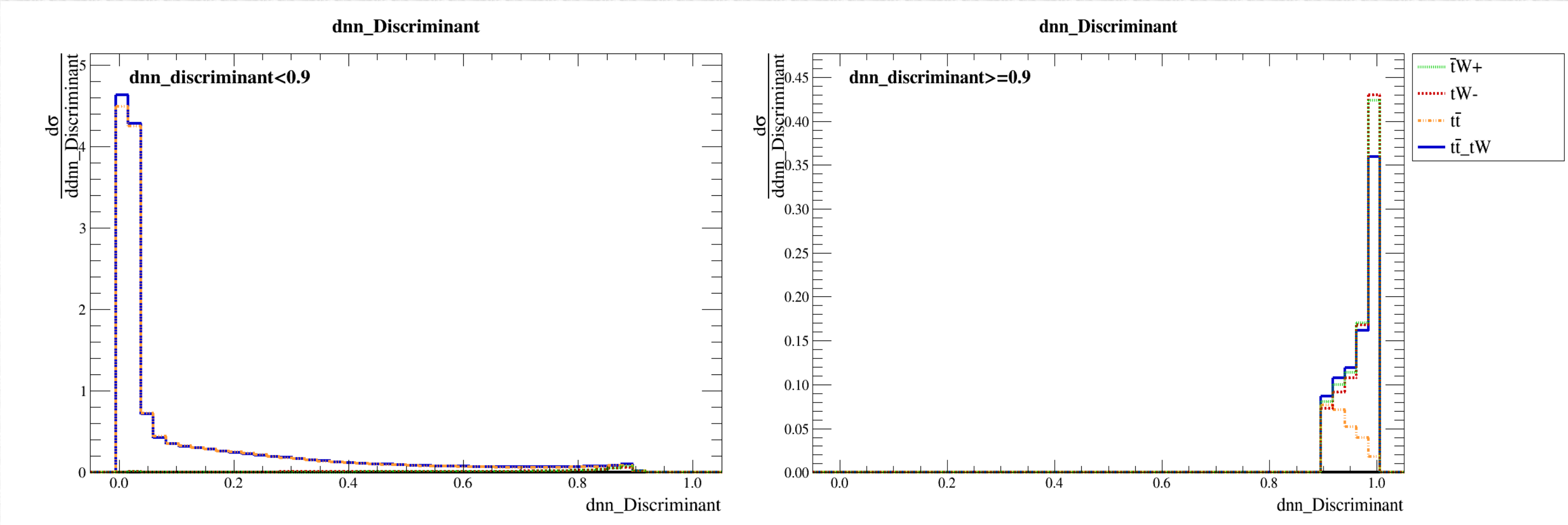


NN separation power

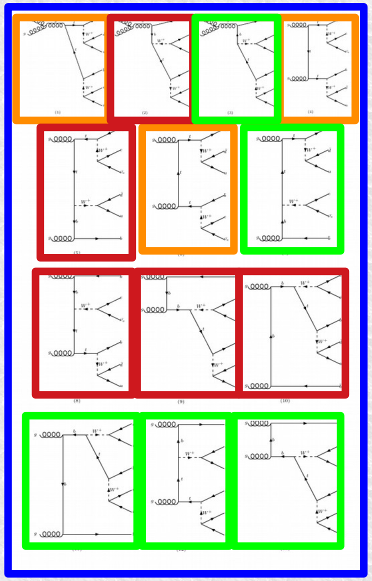
- DNN **successfully separates** double and single resonant contributions to tWb final state
- tT and tW interference “smears” between clasiifed events

DNN results: separation (2)

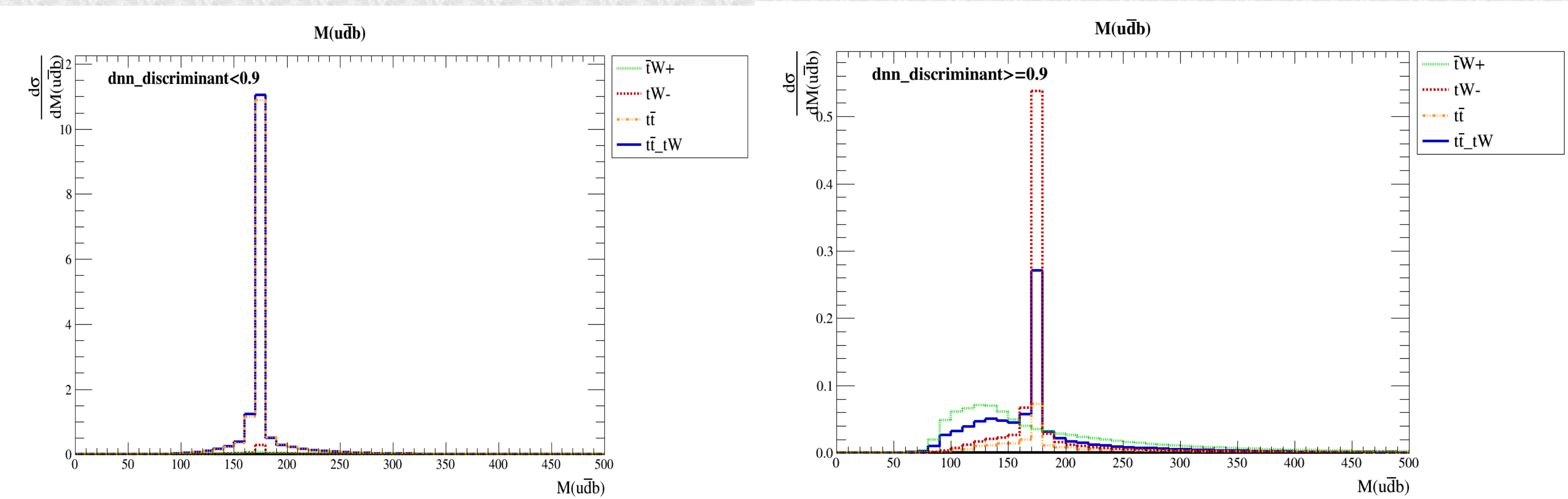
- **DNN discriminant cut**:
  < 0.9: double resonant contribution   >= 0.9: single resonant contribution



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

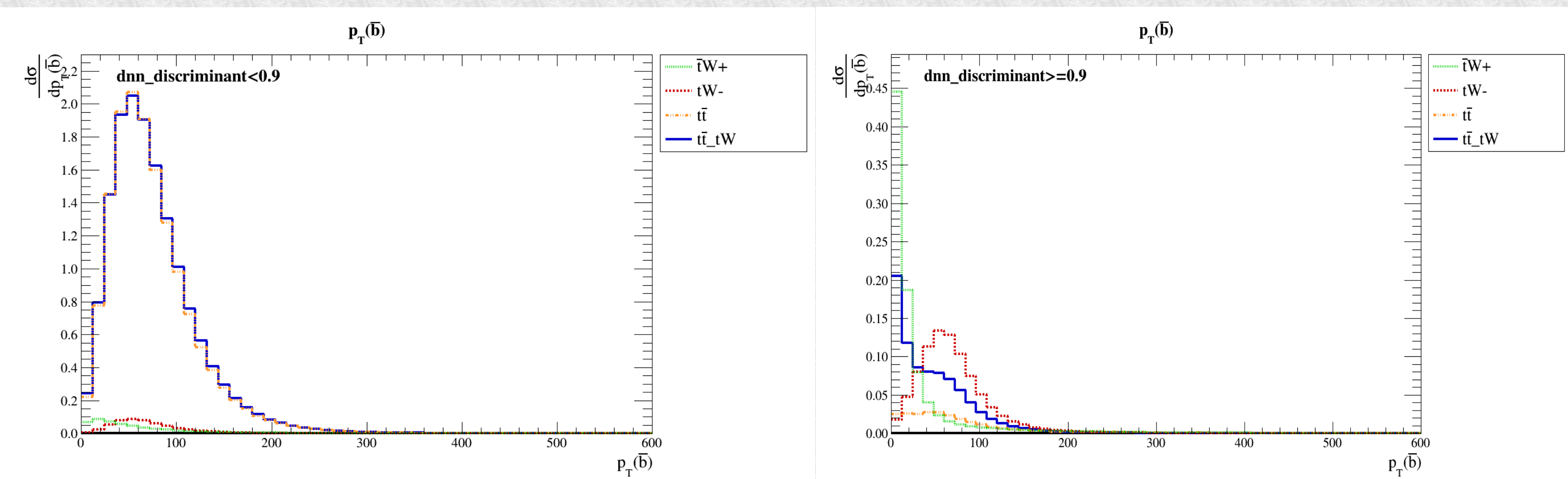


DNN results: distributions



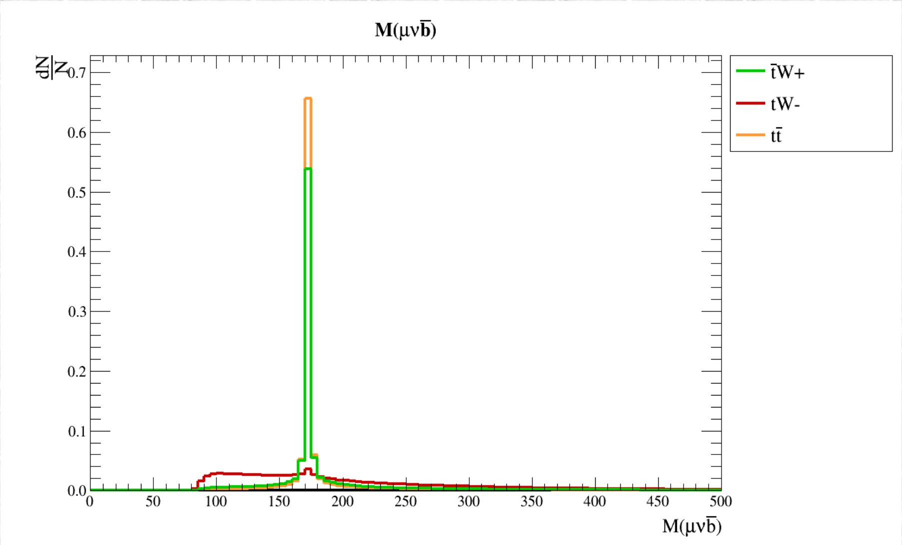
DNN discriminant distribution with DNN discriminant cut

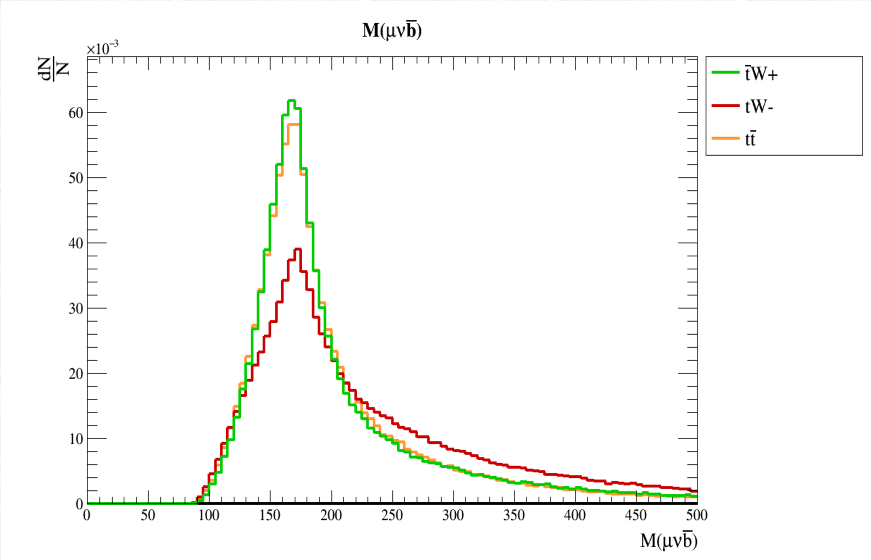
< 0.9 >= 0.9



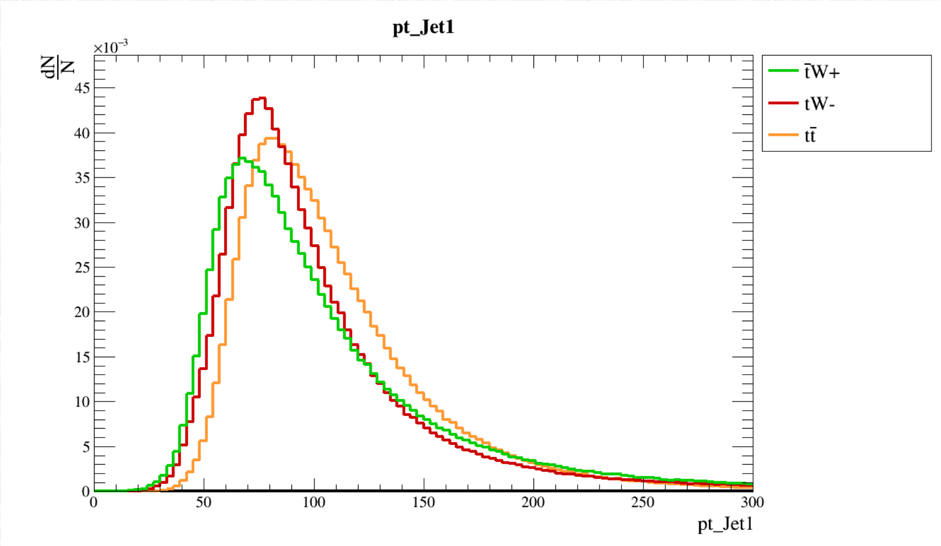
DNN DELPHES kinematic variables

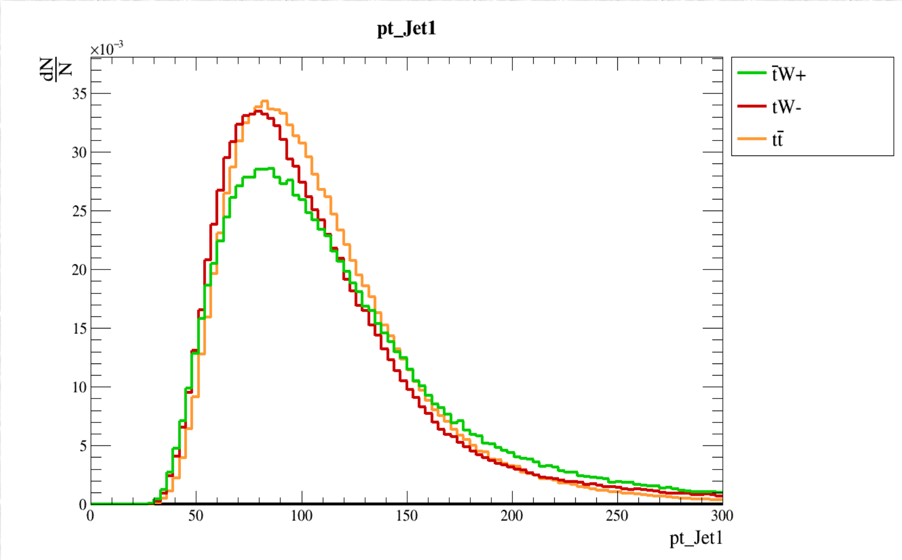
- **Delphes** simulates the detector response, HL-LHC card
- Kinematic variables are blurred:





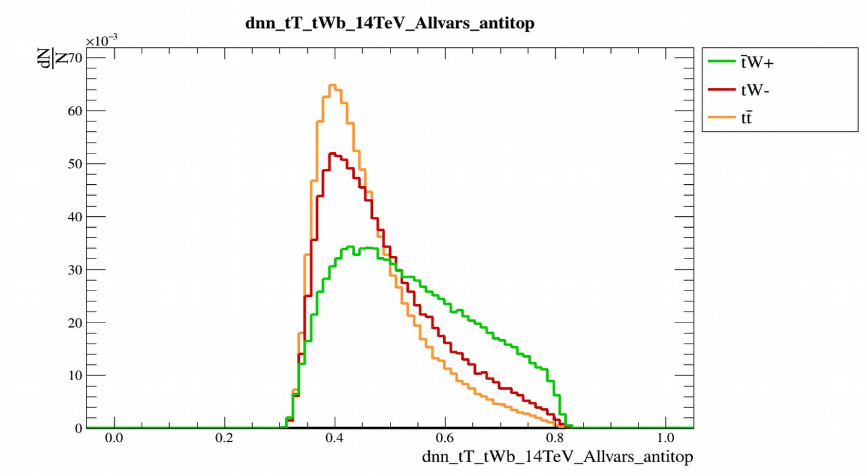
Parton level reconstruction vs DELPHES reconstruction

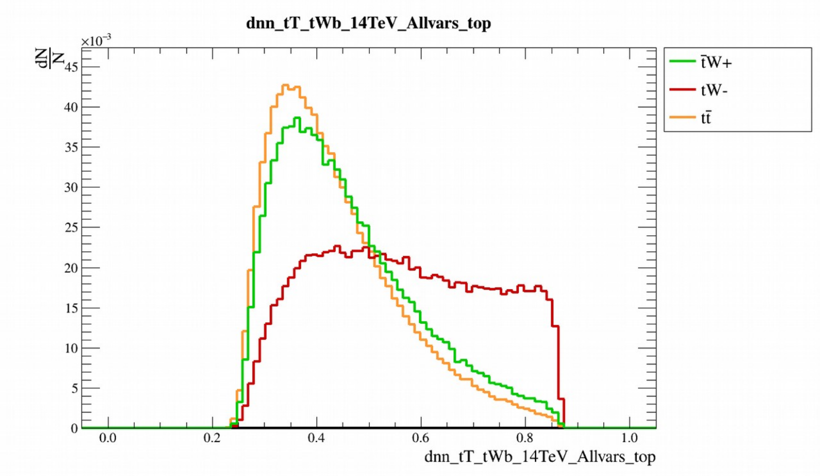




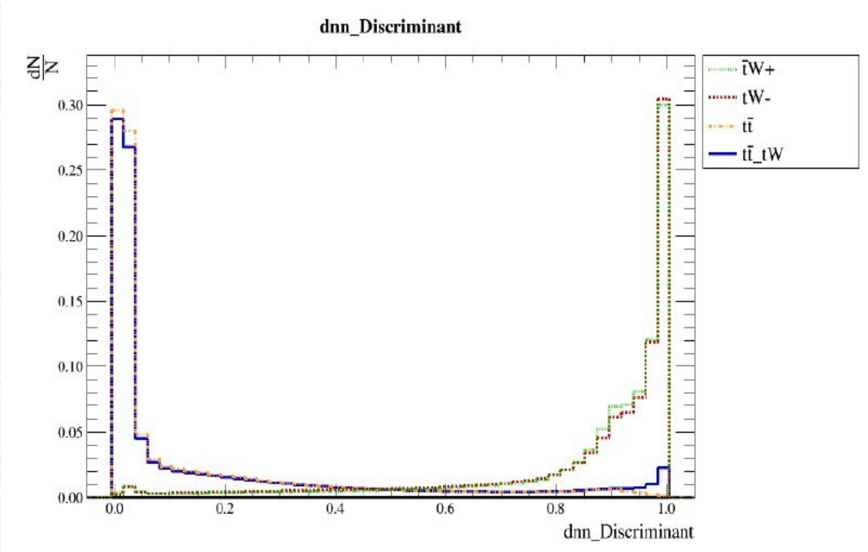
DNN DELPHES results

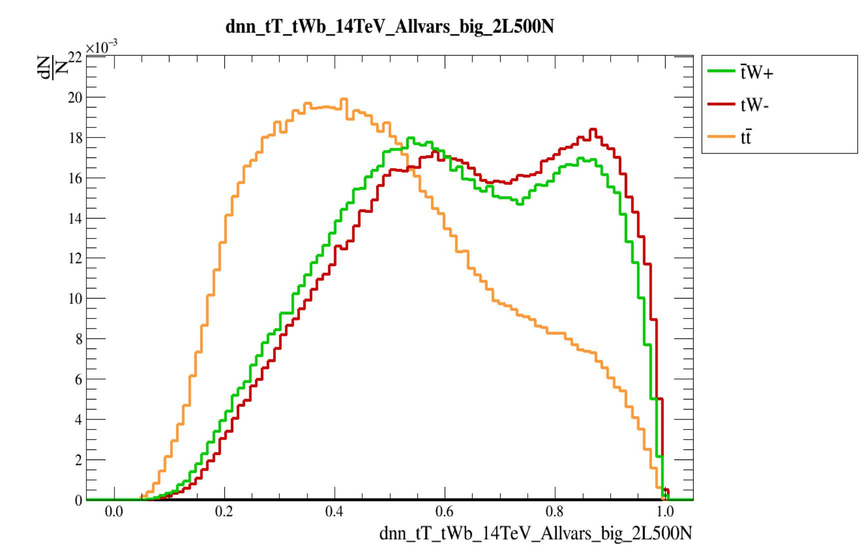
- ParticleFlow jet collections and b-tagged jets =2
- Two DNNs ttbar against top and ttbar against antitop output as kinematic variables





Additional DNN output as kinematic variables





Parton vs DELPHES DNN output distribution

Conclusion

- Neural Network method to separate double and single resonant top production contributions to tWb final state is presented
- Kinematic variables with different behaviour for separating processes are used for DNN training
- DNN successfully separates double and single top quark contributions to tWb final state
- The method has some advantages in comparison to artificial procedures (DR and DS schemes) which are used before
- 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