Measurement of single top quark production in the tW channel and search for s channel in pp collisions at CMS

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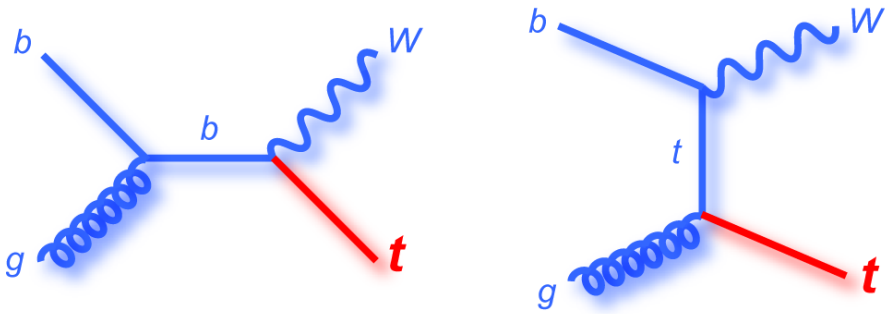
on behalf of the CMS Collaboration

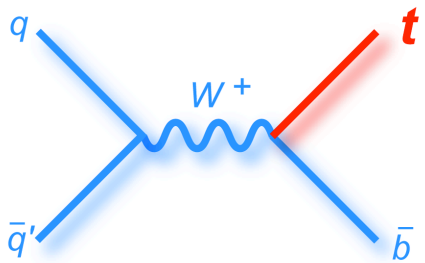
23rd July 2015

Intro: single top quark production in tW and s channels

tW associated



s-channel



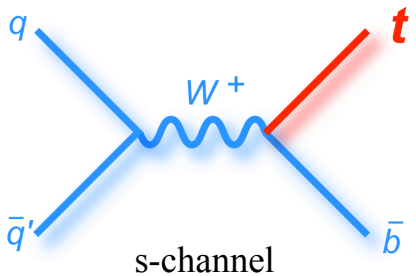
Cross sections (pb) (top mass = 173 GeV)	**tW associated production** approx. NNLO, arXiv:1311.0283, N. Kidonakis	**s-channel** approx. NNLO, arXiv:1311.0283, N. Kidonakis
LHC: pp @ 7 TeV	15.6	4.56
LHC: pp @ 8 TeV	22.2	5.55
LHC: pp @ 13 TeV (top mass = 172.5 GeV)	71.2	11.36
Tevatron $p\bar{p}$ @ 1.96 TeV	0.22	1.04

- **Less abundant than t-channel**
- **s-channel disfavored w.r.t. tW @LHC** (the opposite at Tevatron)
- **tW has the highest cross section increase** with c.m. energy among the single top processes (8 to 13 TeV ~3x as top pair production)

Single top processes and backgrounds

SINGLE LEPTON TOPOLOGY

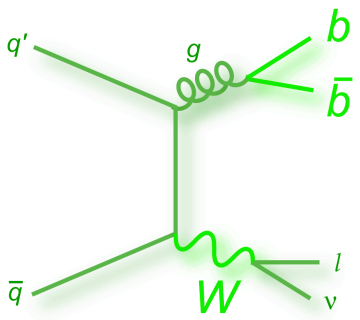
Signals:



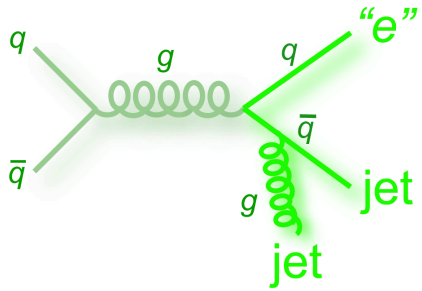
s-channel

Main backgrounds (examples):

W+jets

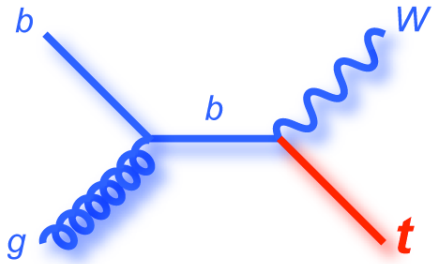


QCD multijet



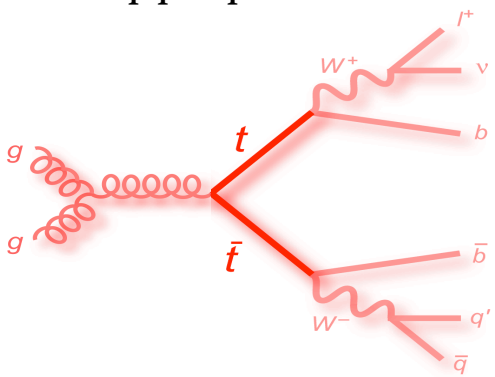
mainly s-channel

DILEPTON TOPOLOGY



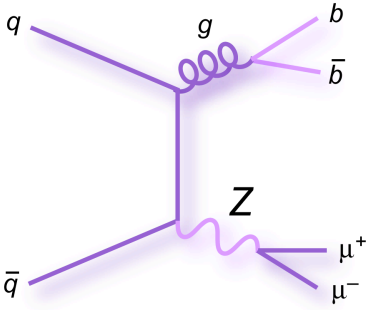
tW associated

top pair production



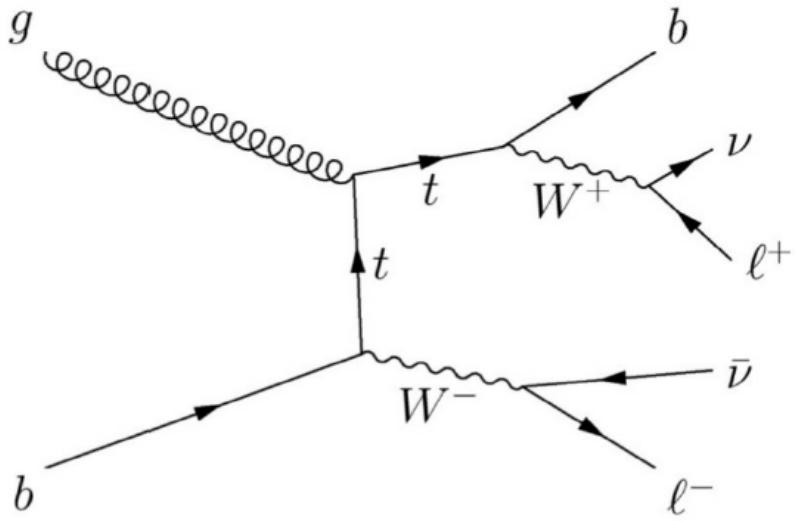
for both channels

Z+jets



mainly for tW production

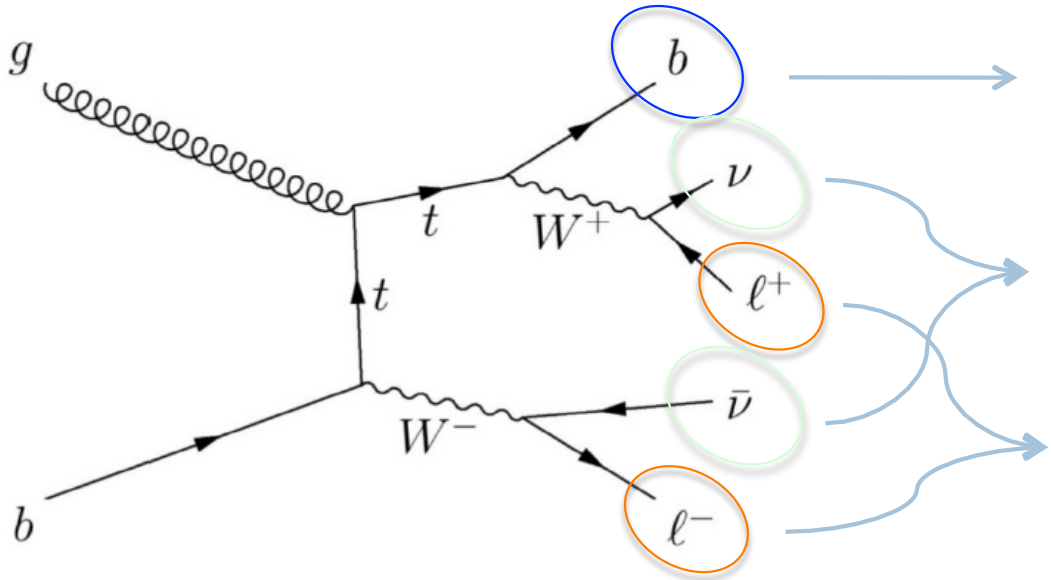
tW associated production: intro



Why is it interesting ?

- Sensitivity to new physics, background for many SUSY searches and Higgs production
- Direct measurement of $|V_{tb}|$
- Strong interference with top pair production (see next slides)

tW associated production: experimental signature and selection



1 jet (coming from b quark)

Missing energy (2 neutrinos)

2 opposite sign isolated leptons

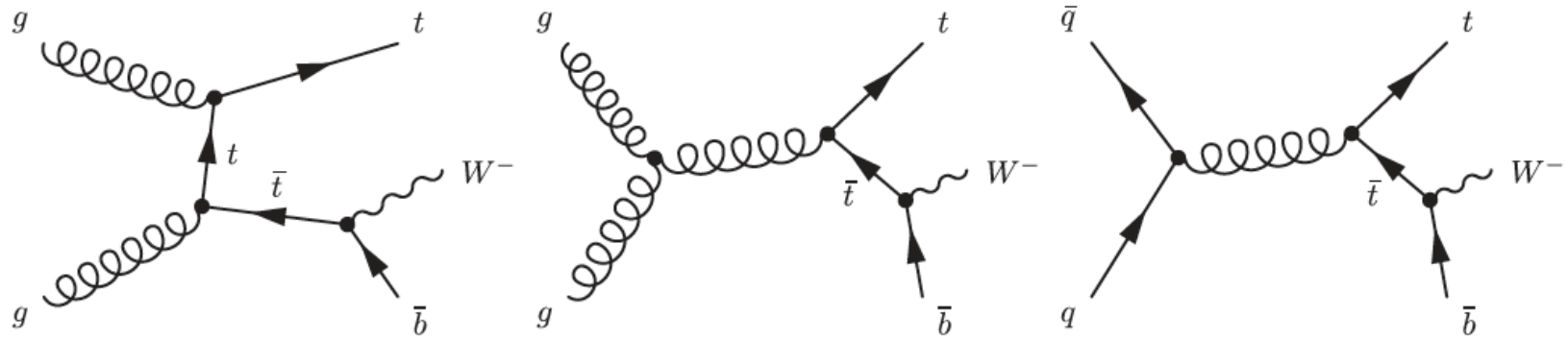
Selection

2 opposite-charge leptons	ee, μμ, eμ with $p_T^l > 20$ GeV
1 jet 1 b-tag	$p_T > 30$ GeV, $\|\eta\| < 2.4$
additional cuts	$E_T^{miss} > 30/50$ GeV @ 7/8 TeV $m_{ll} < 81$ GeV & $m_{ll} > 101$ GeV

tW associated production at NLO

• In **perturbative QCD** the tW associated production at NLO mixes with the top pair production.

• The tW signal is described in the **Diagram Removal (DR)** scheme: all the NLO doubly resonant diagrams are excluded from signal definition.



• The number of predicted signal events using the alternative **Diagram Subtraction (DS)** scheme is consistent with the DR scheme within the statistical uncertainties (difference taken into account as systematic uncertainty).

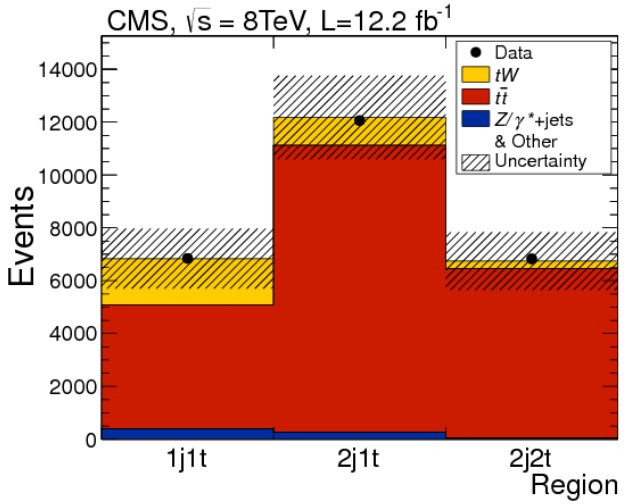
Inclusive cross section @ 8 TeV: BDT and discriminating variables

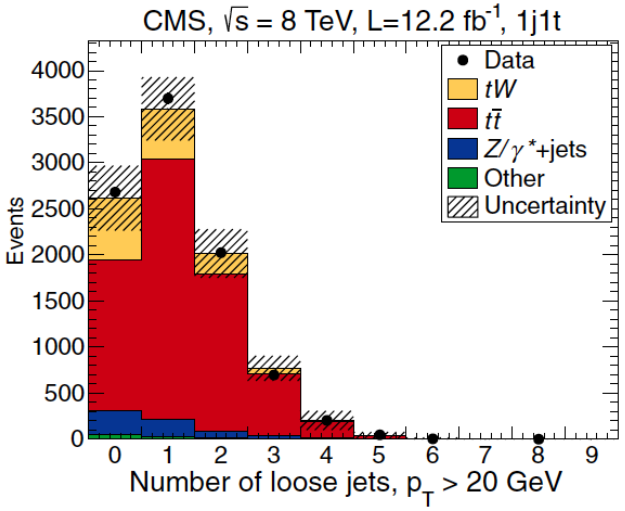
Phys.Rev.Lett. 112, 231802 (2014)

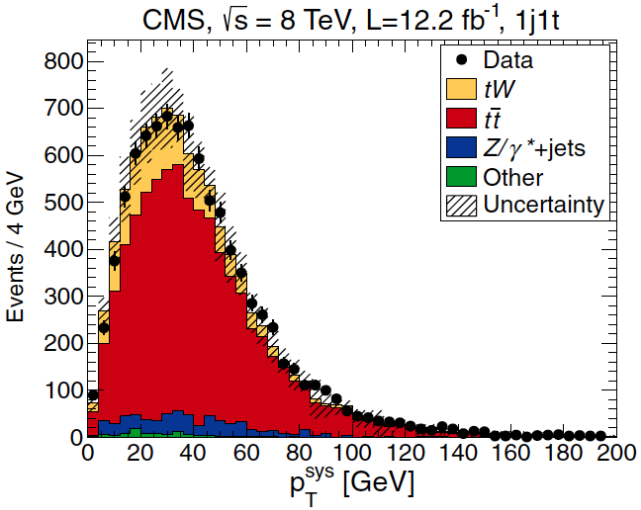
Integrated luminosity = 12.2 fb^{-1}

• **BDT multivariate discriminant** trained in the signal region (1j1t) and in two control regions (2j1t and 2j2t) with 13 variables.

Variable Name	Description
# of loose jets	Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 4.9$
# of central loose jets	Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 2.4$
# of b-tagged loose jets	Number of loose jets, $p_T > 20$ GeV, q_b-tagged, $\|\eta\| < 2.4$
p_T^{sys}	Vector sum of p_T of leptons, jet, and E_T^{miss}
H_T	Scalar sum of p_T of leptons, jet, and E_T^{miss}





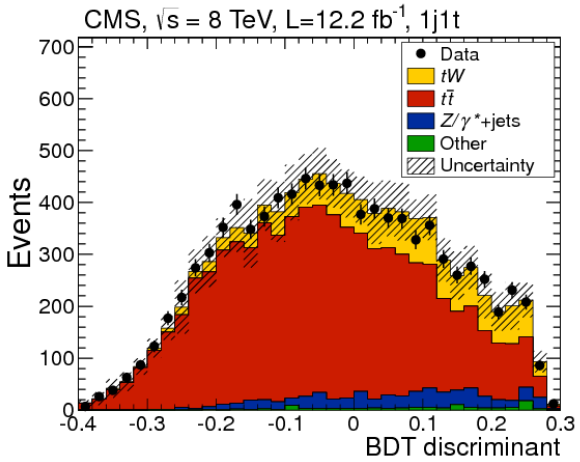


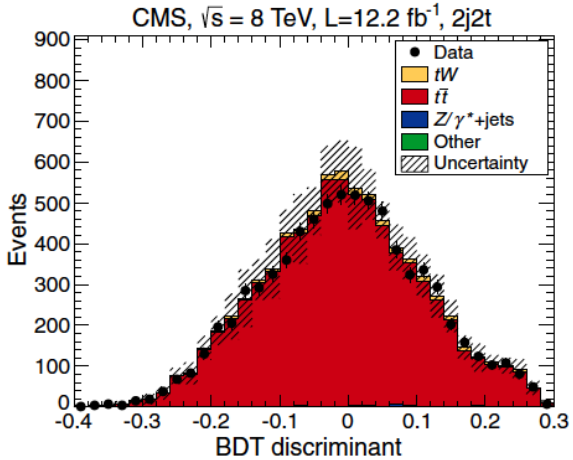
• The loose jet is a jet with $p_T > 20$ GeV, $|\eta| < 4.9$

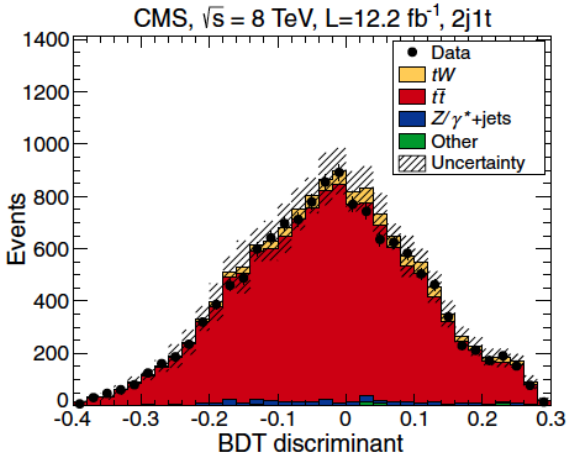
Inclusive cross section @ 8 TeV: results

Phys.Rev.Lett. 112, 231802 (2014)

• **Simultaneous binned likelihood fit to the BDT** for the three final states in the signal and control regions (which allow for better determination of top pair contribution and help to constrain the b-tagging and JES uncertainties on the measurement)







σ_{tW} = 23.4 ± 5.4 pb

significance = 6.1σ

($5.4^{+1.5}_{-1.4}$ σ expected)

σ_{tW}= 22.2 ±0.6±1.4 pb, SM expectation

Assuming the CKM matrix elements $|V_{td}|$ and $|V_{ts}| << |V_{tb}|$, $|V_{tb}| = \sqrt{\sigma/\sigma_{th}}$:

$|V_{tb}| = 1.03 \pm 0.12(exp.) \pm 0.04(th.)$

Inclusive cross section @ 8 TeV: systematic uncertaintes and combination with ATLAS

Phys.Rev.Lett. 112, 231802 (2014) - ATLAS

CMS-PAS-TOP-14-009 - CMS

Systematic uncertainty sources and their impact on the cross section measurement

Systematic uncertainty	$\Delta\sigma$ (pb)	$\Delta\sigma/\sigma$
ME/PS matching thresholds	3.3	14%
Renormalization/factorization scale	2.9	12%
Top-quark mass	2.2	9%
Fit statistical	1.9	8%
Jet energy scale	0.9	4%
Luminosity	0.7	3%
Z+jets data/simulation scale factor	0.6	3%
tW DR/DS scheme	0.5	2%
$t\bar{t}$ cross section	0.4	2%
Lepton identification	0.4	2%
PDF	0.4	2%
Jet energy resolution	0.2	1%
b-tagging data/simulation scale factor	0.2	<1%
$t\bar{t}$ spin correlations	0.1	<1%
Pileup	0.1	<1%
Top-quark p_T reweighting	0.1	<1%
E_T^{miss} modeling	0.1	<1%
Lepton energy scale	0.1	<1%
Total	5.5	24%

ATLAS-CMS combination

$\sigma_{tW} = 27.2 \pm 5.8$ pb *ATLAS*

$\sigma_{tW} = 23.4 \pm 5.4$ pb *CMS*

$\sigma_{tW} = 25.0 \pm 1.4\ (\text{stat.}) \pm 4.4\ (\text{syst.}) \pm 0.7\ (\text{lumi.})$ pb

$= 25.0 \pm 4.7$ pb **COMBINED**

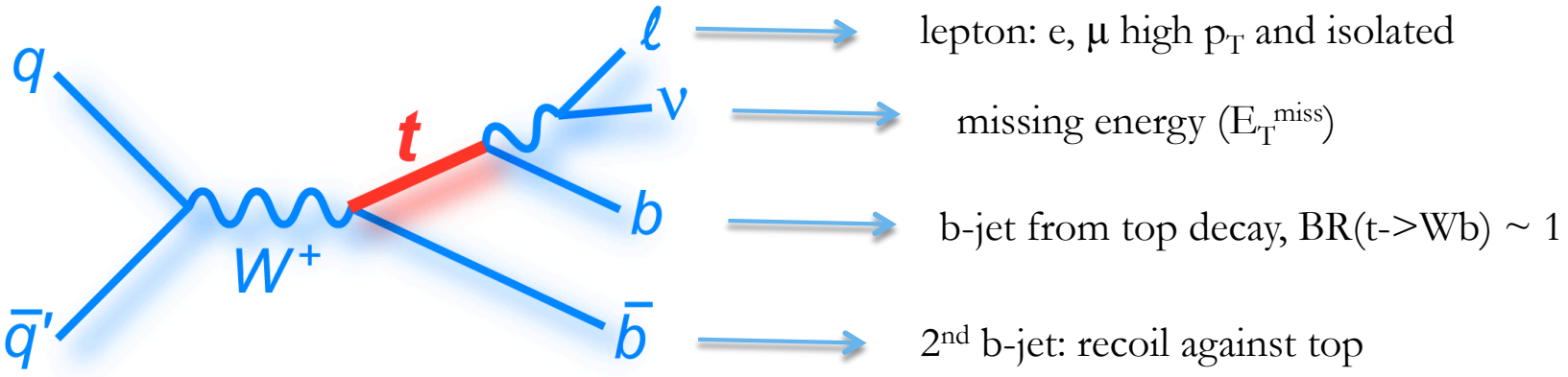
Process negligible at Tevatron,
LHC observation at 8 TeV

s-channel inclusive cross section: intro

- **Smallest cross section at the LHC** among the single top processes

- **Sensitive to non-SM mediators** like W' or charged Higgs bosons

- **Observation at Tevatron** (2014, PRL **112**, 231803); **ATLAS** set upper limits at 7 TeV (2011) and 8 TeV (2015, PLB **740**, 118)



N.B. the jet coming from b-quark has broader η
w.r.t. the jet stemming from anti-b-quark

s-channel inclusive cross section: selection

PAS-CMS-TOP-13-009

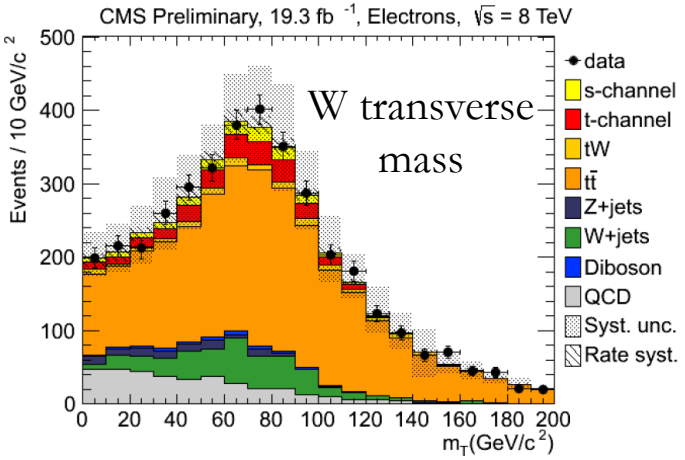
1 muon or electron — $p_T^{\mu} > 26$ GeV, $p_T^{e} > 30$ GeV

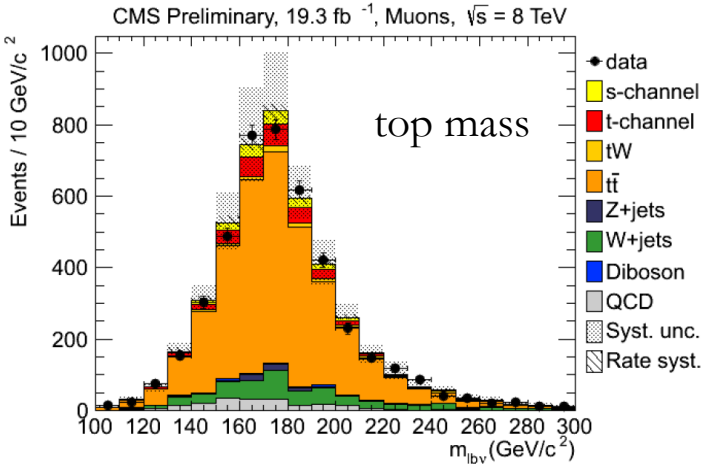
2 jets 2 b-tagged — $p_T > 40$ GeV

additional cuts ($t\bar{t}$ background rejection) — veto other jets with $p_T > 30$ GeV

Process	μ 2-jets 2-tags
$t\bar{t}$	3144 ± 189
$W + jets$	449 ± 93
$Z + jets$	65 ± 20
Diboson	45 ± 10
QCD	209 ± 52
tW	102 ± 11
t-channel	271 ± 18
s-channel	168 ± 10
Total MC	4455 ± 286
Data	4450

Uncertainties include stats., bkg rates and b-tagging





Top quark reconstruction: take the b-jet for which the reconstructed top mass is the closest to 172.5 GeV

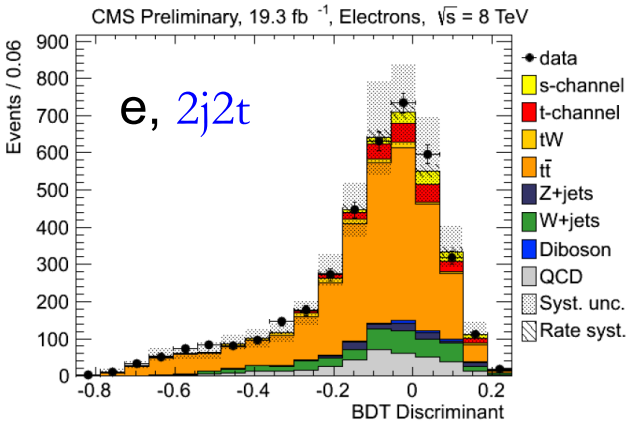
Exploit the different topology of the signal and backgrounds using a **multivariate classification approach** (Boosted Decision Trees)

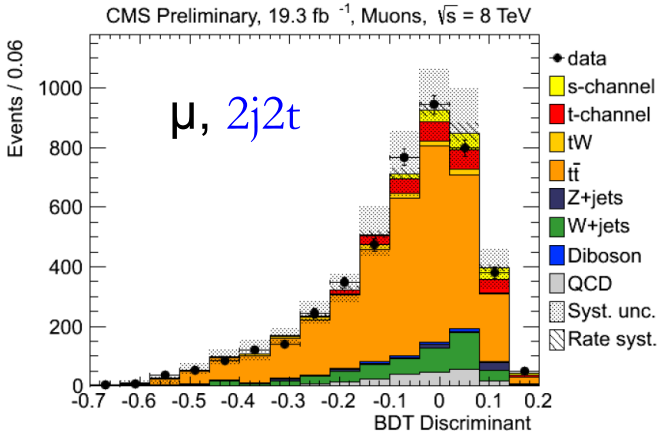
s-channel inclusive cross section @ 8 TeV: BDT and QCD estimation

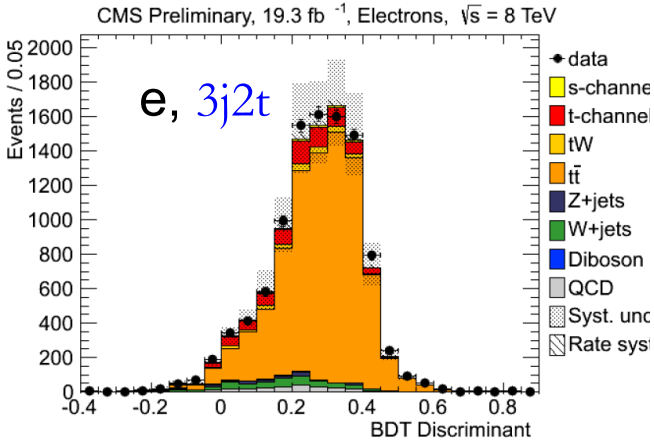
CMS-TOP-13-009

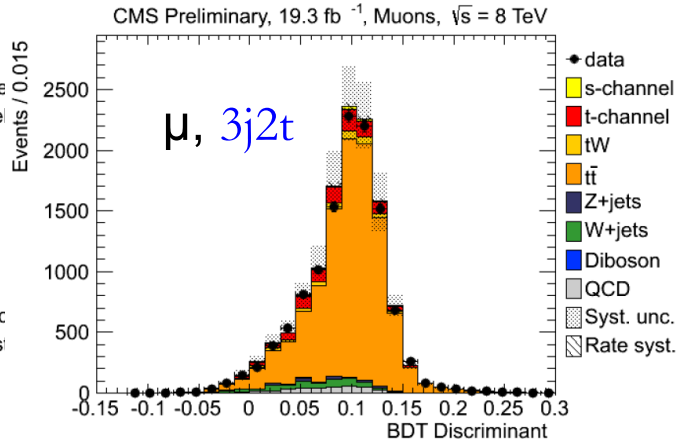
Integrated luminosity = 19.3 fb^{-1}

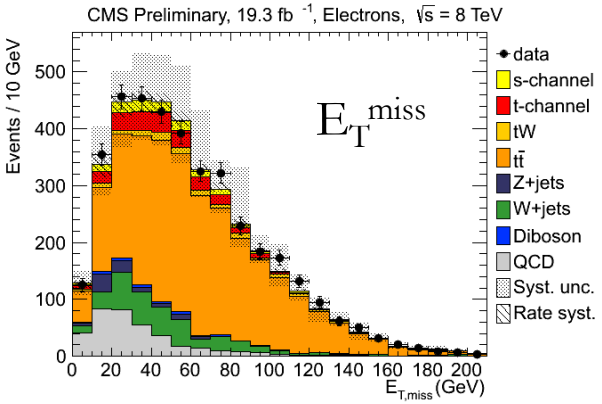
• **Training of BDT discriminants** in muon and electrons channels in signal (**2j2t**) and tt̄ enriched control sample (**3j2t**)











Multi-jets QCD estimation: maximum likelihood template fit to W transverse mass and E_T^{miss} distributions to extract the amount of QCD events in the signal sample (template taken from a control sample on data obtained inverting the lepton relative isolation requirement)

s-channel inclusive cross section @ 8 TeV: signal extraction

CMS-TOP-13-009

• **Signal extraction:** binned maximum likelihood fit to the BDT discriminant distribution, simultaneously in the signal and control regions. $t\bar{t}$ and W+jets backgrounds constrained in the fit as well.

Upper limit: $\sigma_{s\text{-chan}} < 11.5\ (17.0, 9.0)$ pb @ 95% CL,

Assuming SM signal $\sigma_{s\text{-chan}} = 6.2^{+8.0}_{-5.1}$ pb (68% FC interval)

UL observed (expected with SM signal, expected with bkg only)

$\sigma_{s\text{-channel}} = 5.55 \pm 0.08 \pm 0.21$ pb, SM expectation

• **Main uncertainties:** $t\bar{t}$ and W+jets ren./fact. scales (~80%) which could be improved with NLO $t\bar{t}$ generators, JES (~50%), PS-ME matching thresholds (32%)

details in my poster !

Conclusions and outlook

• **tW associated production:**
cross section measurement and observation established at 8 TeV, $|V_{tb}|$ determination

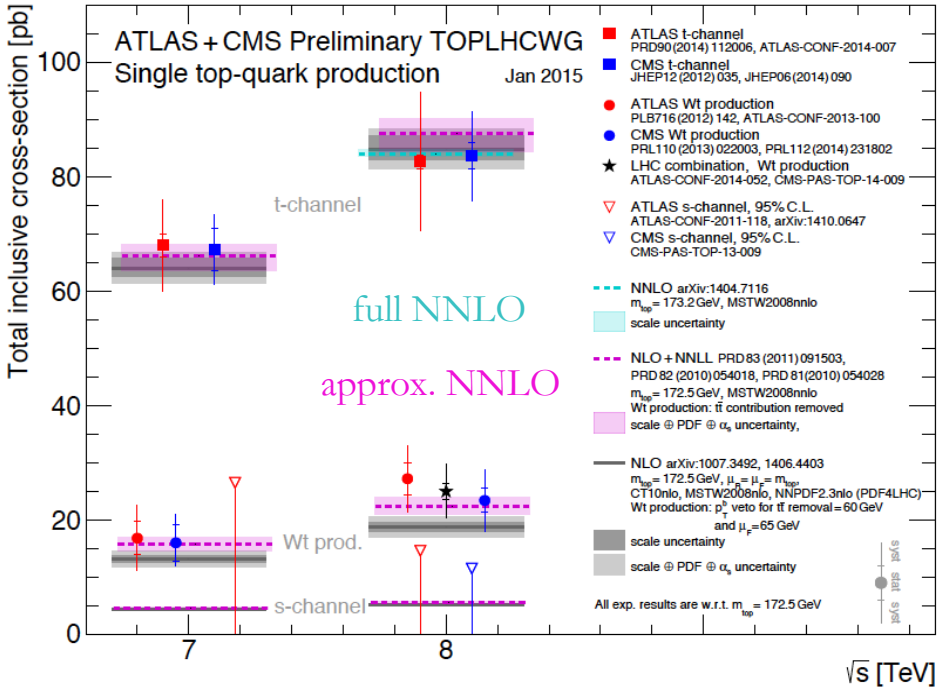
- at 13 TeV the increase in cross section is comparable to top pair production (~3x)

- measurement of $t\bar{t}$ / tW interference

• **s-channel production upper limit**

- disfavored at 13 TeV: not for early data

- combination 7+8 TeV data, use of more control regions to constrain the backgrounds, possibly move to NLO $t\bar{t}$ generators to benefit from reduced scale uncertainty



Good agreement with the approx. NNLO calculations (full NNLO for t-channel)

Backup

Inclusive cross section @ 7 TeV

Phys.Rev.Lett 110, 022003 (2013)

Integrated luminosity = 4.9 fb^{-1}

• **Fit to a BDT multivariate discriminant** simultaneously in the signal region (1j1t) and in control regions (2j1t and 2j2t), $t\bar{t}$ background dominated. The control regions help to constrain the b-tagging and JES uncertainties on the measurement.

• **Results**

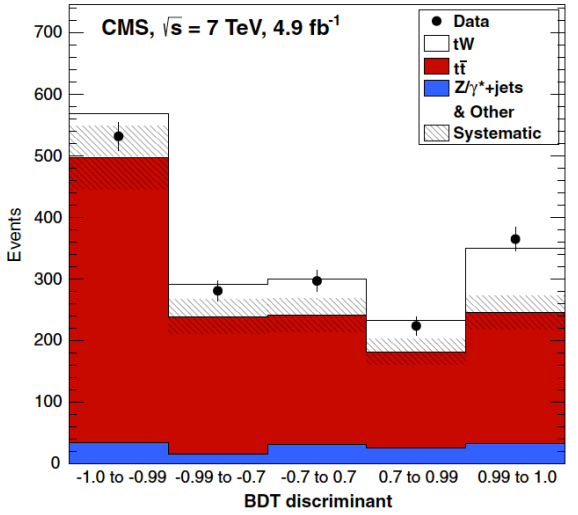
$$\sigma_{tW} = 16\ ^{+5}_{-4}\ pb$$

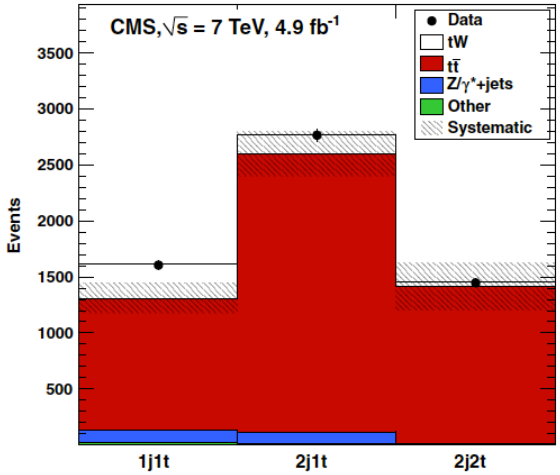
$$|V_{tb}| = 1.01\ ^{+0.16}_{-0.13}\ (exp.)\ ^{+0.03}_{-0.04}(th.),$$

Significance = 4.0σ ($3.6\ ^{+0.8}_{-0.9}\ \sigma$ expected)

SM expectation: $\sigma_{tW} = 15.6 \pm 0.4 \pm 1.1$ pb

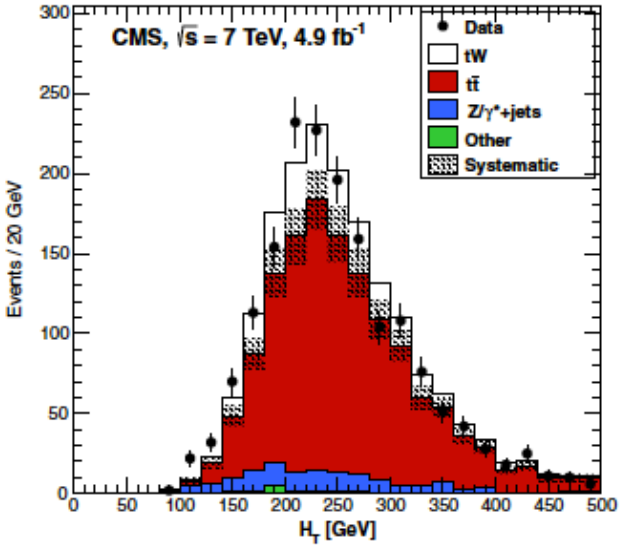
• **Main uncertainties**: statistical (21%), jet energy scale (15%), matching thresholds (10%)

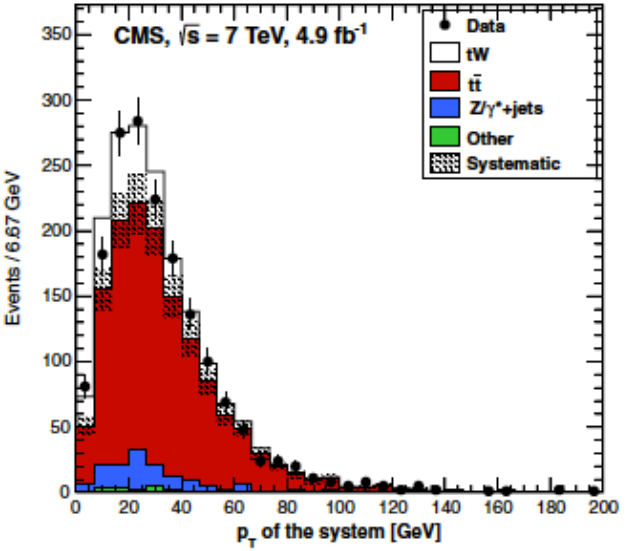




tW-associated @ 7 TeV

Systematic Uncertainty	$\Delta\sigma$ (pb)	$\frac{\Delta\sigma}{\sigma}$
Luminosity	0.69	0.04
Pileup modeling	0.24	0.02
Electron trigger efficiency	0.35	0.02
Muon trigger efficiency	0.38	0.02
Electron identification	0.70	0.04
Muon identification	0.45	0.03
b-tagging	0.30	0.02
Jet Energy Scale	2.42	0.15
Jet Energy Resolution	0.58	0.04
E_T^{miss} modeling	0.40	0.05
tW Q^2	0.34	0.02
$t\bar{t}$ Q^2	0.29	0.02
ME/PS Matching Thresholds	1.62	0.10
tW DR/DS scheme	0.94	0.06
PDF uncertainties	0.34	0.02
$t\bar{t}$ cross section	0.96	0.06
$Z/\gamma^\star$ modeling	0.67	0.04
Statistical	3.33	0.21
Total	4.95	0.31





tW-associated @ 8 TeV

BDT input variables

Variable Name	Description
# of loose jets	Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 4.9$
# of central loose jets	Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 2.4$
# of b-tagged loose jets	Number of loose jets, $p_T > 20$ GeV, q_b-tagged, $\|\eta\| < 2.4$
p_T^{sys}	Vector sum of p_T of leptons, jet, and E_T^{miss}
H_T	Scalar sum of p_T of leptons, jet, and E_T^{miss}
p_T(jet)	p_T of the leading, tight, b-tagged jet
p_T(loose jet)	p_T of leading loose jet, defined as 0 for events with no loose jet present
p_T^{sys}/H_T	Ratio of p_T^{sys} to H_T for the event
m_{sys}	Invariant mass of the combination of the leptons, jet, and E_T^{miss}
Centrality(j$\ell\ell$)	Centrality of jet and leptons, defined as ratio of transverse to total energy
H_T(leptons)/H_T	Ratio of scalar sum of p_T of the leptons to the H_T of full system
p_T(j$\ell\ell$)	Vector sum of p_T of jet and leptons
E_T^{miss}	Missing transverse energy in the event

systematic uncertainties table

Systematic uncertainty	$\Delta\sigma$ (pb)	$\Delta\sigma/\sigma$	Notes
ME/PS matching thresholds	3.3	14%	Matching threshold 2× and 1/2× nominal 20 GeV value in $t\bar{t}$ simulation
Renormalization/factorization scale	2.9	12%	Scale value 2× and 1/2× nominal value of $m_t^2 + \sum p_T^2$ in $t\bar{t}$ and tW simulation
Top-quark mass	2.2	9%	m_t varied in tW and $t\bar{t}$ simulation by ±2 GeV
Fit statistical	1.9	8%	Remaining uncertainty in fit when all other systematic uncertainties are removed
Jet energy scale	0.9	4%	Jet energy scale varied up/down
Luminosity	0.7	3%	2.6% uncertainty in the measured luminosity
Z+jets data/simulation scale factor	0.6	3%	Varying scale factors used for correcting Z+jets E_T^{miss} simulation
tW DR/DS scheme	0.5	2%	Difference between DR and DS scheme used for defining tW signal
$t\bar{t}$ cross section	0.4	2%	Uncertainty in the cross section of $t\bar{t}$ production
Lepton identification	0.4	2%	Uncertainty in scale factors for lepton efficiencies between data/simulation
PDF	0.4	2%	From choice of PDF
Jet energy resolution	0.2	1%	Energy resolution for jets varied up/down
b-tagging data/simulation scale factor	0.2	<1%	Variations in scale factors
$t\bar{t}$ spin correlations	0.1	<1%	Difference between $t\bar{t}$ simulation with/without spin correlations
Pileup	0.1	<1%	Varying effect of pileup
Top-quark p_T reweighting	0.1	<1%	Uncertainty due to differences in top quark p_T between data and $t\bar{t}$ simulation
E_T^{miss} modeling	0.1	<1%	Uncertainty in amount of unclustered E_T^{miss}
Lepton energy scale	0.1	<1%	Uncertainty in energy of leptons
Total	5.5	24%	

tW-associated @ 8 TeV: Combination

Category	ATLAS		CMS		ρ
Data statistics	Data statistics	7.1%	Fit statistics	8.1%	0.0
Category subtotal		**7.1%**		**8.1%**	**0.0**
Simulation statistics	Sim. statistics	2.8%	Sim. statistics	2.4%	0.0
Category subtotal		**2.8%**		**2.4%**	**0.0**
Luminosity		3.7%		3.0%	—
Category subtotal		**3.7%**		**3.0%**	**0.31**
Theory modeling	ISR/FSR	5.9%	Ren./fact. scale	12.4%	1.0
	tW gen. and PS	11.0%			—
	$t\bar{t}$ gen. and PS	7.5%	ME/PS match. thr.	14.1%	1.0
	PDF	2.5%	PDF	1.7%	1.0
	$tW/t\bar{t}$ overlap	1.4%	DR/DS scheme	2.1%	1.0
			Top p_T reweight.	0.4%	—
Category subtotal		**14.8%**		**19.0%**	**0.66**
Background normalization	bkg. mod.	3.6%	$t\bar{t}$ cross section	1.7%	0.0
			Z+jets	2.6%	—
Category subtotal		**3.6%**		**3.1%**	**0.0**
Jets	JES common	10.0%	JES	3.8%	0.0
	JES flavour	5.0%			—
	Jet id	0.2%			—
	Jet res.	0.7%	Jet resolution	0.9%	0.0
Category subtotal		**11.2%**		**3.9%**	**0.0**
Detector modeling	Lepton modeling	2.4%	Lepton modeling	1.8%	0.0
	MET scale	4.1%	MET modeling	0.4%	0.0
	MET resolution	4.5%			—
	b-tagging	8.4%	b tagging	0.9%	0.5
			Pileup	0.4%	—
Category subtotal		**10.6%**		**2.0%**	**0.17**
Total		**23.3%**		**21.7%**	**0.38**

s-channel @ 8 TeV: event yield table

Process	μ 3-jets 2-tags	μ 2-jets 2-tags	e 3-jets 2-tags	e 2-jets 2-tags
$t\bar{t}$	10043 ± 604	3144 ± 189	8010 ± 494	2483 ± 154
$W + jets$	446 ± 92	449 ± 93	370 ± 76	361 ± 77
$Z + jets$	112 ± 32	65 ± 20	97 ± 29	89 ± 27
Diboson	36 ± 8	45 ± 10	33 ± 7	37 ± 8
QCD	353 ± 74	209 ± 52	222 ± 19	363 ± 69
tW	336 ± 28	102 ± 11	259 ± 22	105 ± 11
t-channel	949 ± 61	271 ± 18	750 ± 49	217 ± 15
s-channel	87 ± 5	168 ± 10	70 ± 4	131 ± 8
Total MC	12361 ± 750	4455 ± 286	9811 ± 606	3786 ± 253
Data	11979	4450	10149	3884

s-channel @ 8 TeV: fit results by channel

$$\sigma_{\text{s-ch.}} = 5.9 \pm 7.1(\text{exp.}) \pm 5.0(\text{th.})\ \text{pb} = 5.9 \pm 8.7\ \text{pb}\ \text{muon channel}$$
$$\sigma_{\text{s-ch.}} = 6.9 \pm 5.6(\text{exp.}) \pm 6.5(\text{th.})\ \text{pb} = 6.9 \pm 8.7\ \text{pb}\ \text{electron channel}$$
$$\sigma_{\text{s-ch.}} = 6.2 \pm 5.4(\text{exp.}) \pm 5.9(\text{th.})\ \text{pb} = 6.2 \pm 8.0\ \text{pb}\ \text{combined}$$

$$\sigma_{\text{s-ch.}} = 5.9^{+8.6}_{-5.1}\ \text{pb}\ \text{muon channel}$$
$$\sigma_{\text{s-ch.}} = 6.9^{+8.7}_{-5.7}\ \text{pb}\ \text{electron channel}$$
$$\sigma_{\text{s-ch.}} = 6.2^{+8.0}_{-5.1}\ \text{pb}\ \text{combined}$$

$$\sigma_{s\text{-ch.}} < 12.4 \quad (18.4,\ 10.5)\ \text{pb} \quad \text{muon channel}$$
$$\sigma_{s\text{-ch.}} < 14.7 \quad (23.2,\ 15.4)\ \text{pb} \quad \text{electron channel}$$
$$\sigma_{s\text{-ch.}} < 11.5 \quad (17.0,\ 9.0)\ \text{pb} \quad \text{combined}$$

s-channel @ 8 TeV: BDT input variables

2j2t BDT input variables electron channel

Variable	Description
m_T	tranverse W-boson mass
$\Delta\Phi_{top,b'}$	difference in azimuthal angle between top and recoiled b-tagged jet
$\not{E}_T$	missing transverse energy
$M_{\ell b2}$	invariant mass of the lepton and the second-to-leading b-tagged jet
$\cos\theta^*$	cosine of the angle between the lepton and the b-tagged jet recoiling against the top-quark, in the top rest frame
p_T^{bb}	vector sum of p_T of the two b-tagged jets
$\Delta R_{bb}(*)$	angular separation between the two b-tagged jets
p_T^{ℓ}	transverse momentum of the lepton
$m_{\ell\nu b}$-best	invariant mass of lepton, neutrino and one of the b-tagged jets reconstructed with the best-mass top method, as described in Sec.2
$\Delta R_{b'\ell}$	angular separation between the b-tagged jet recoiling against the top quark and the lepton
H_T	scalar sum of p_T of all jets

(*) $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

2j2t BDT input variables muon channel

Variable	Description
p_T^{bb}	vector sum of p_T of the two b-tagged jets
$m_{\ell\nu b}$-best	invariant mass of lepton, neutrino and one of the b-tagged jets reconstructed with the best-mass top method, as described in Sec.2
m_T	tranverse W-boson mass
$M_{\ell b2}$	invariant mass of the lepton and the second-to-leading b-tagged jet
$\not{E}_T$	missing transverse energy
$\Delta\Phi_{top,b'}$	difference in azimuthal angle between top and the recoiled b-tagged jet
$\cos\theta_l$	cosine of the angle between the lepton and the beam axis in top-quark rest frame
ΔR_{bb}	angular separation between the two b-tagged jets
H_T	scalar sum of p_T of all jets
p_T^{ℓ}	transverse momentum of the lepton