Single Top Quark Production Measurements in CMS

OLOMOUC, CZECH REPUBLIC

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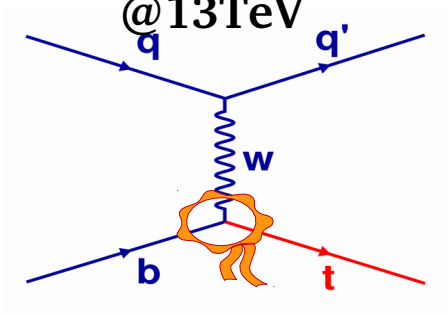
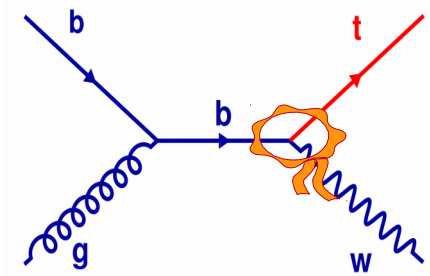
Single Top

- **Single Top production mechanisms:**
  - t-channel
  - W associated
  - s-channel
- **Production via Electroweak interactions.**
  - Study of Wtb coupling
  - Measurement of vtb
  - Polarized sample, measuring top polarization
- **Sensitive to new physics**
  - Anomalous coupling(FCNC)
  - Charged Higgs Models
- **Sensitive to PDF**

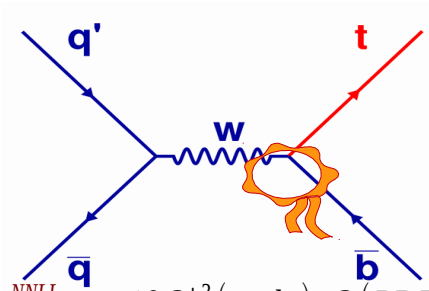
@13TeV



$$\sigma^{NNLL}_{t-channel} = 217^{+7}_{-5}(scale) \pm 6(PDF)$$



$$\sigma^{NNLL}_{W\,associated} = 62.2^{+3}_{-4}(scale) \pm 5(PDF)$$



$$\sigma^{NNLL}_{s-channel} = 10.3^{+3}_{-2}(scale) \pm 3(PDF)$$

Outline

t-channel measurements:

- Inclusive cross section @ 13TeV (paper in preparation)
- Fiducial cross section @ 8TeV (TOP-15-007)
- Differential cross section @ 13TeV (TOP-16-004)

s-channel measurement:

- Search @ 7,8TeV (JHEP09(2016)027)

Association production of Z boson and single Top(SM):

- Search @ 8TeV (TOP-12-039)

Do not cover tW channel

- observation @ 8TeV (PRL 112 (2014) 231802)

- See also
  - **Properties in single top: talk by J. Pena (ATLAS)**
  - **FCNC talk: by J. Espinosa (ATLAS)**

NEW t-channel Inclusive Cross Section, TOP-16-003 (Paper in prep.)

Trigger:
Isolated muon with p_T >20 GeV

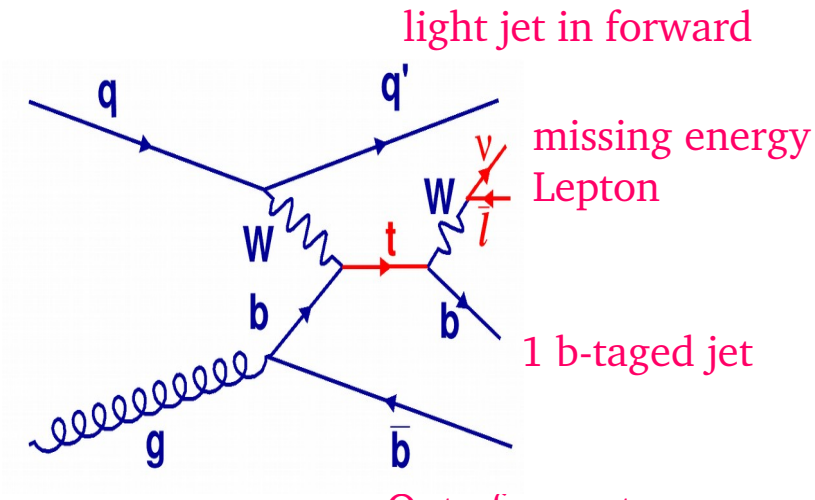
Muon:
p_T > 22 GeV, $|\eta|$ < 2.1, I_{rel} < 0.06.

Veto lepton:
p_T> 10 (20) GeV, $|\eta|$ < 2.5, I_{rel} < 0.2 for μ(e)

Jet: anti-kT, R=0.4
$|\eta|$ < 4.7 and p_T> 40 GeV

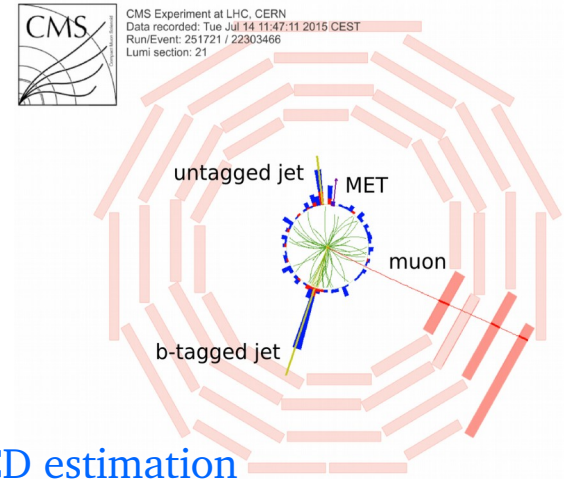
b-tagging:
eff_b: 45%, $eff_{fake,light\ jet}$: 0.1%

QCD rejection:
$m_T(W)$ > 50GeV



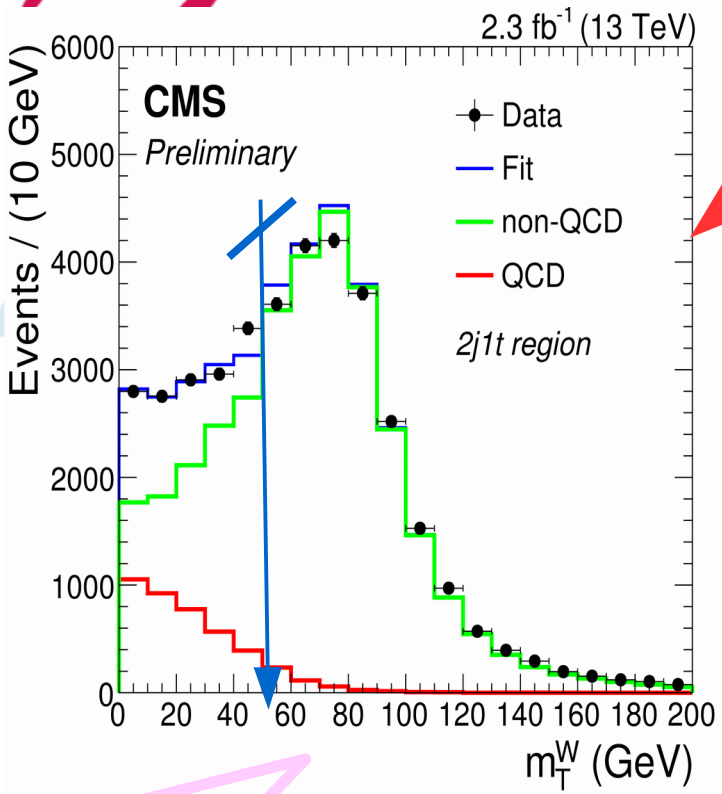
2 jets, 1b-tagged jet (2-jets 1-tag)

2-jets 1-tag	Signal Region
3-jets 2-tags	$t\bar{t}$ Control Region
3-jets 1-tag	$t\bar{t}$ Control Region
2-jets 0-tag	Wjets Control Region QCD estimation validation



Events with non-isolated lepton and low $m_T(W)$ are used in QCD estimation

t-channel Inclusive Cross Section, TOP-16-003 (Paper in prep.)



Data Driven QCD Estimation:

- Fit in each signal and control region, removing selection on $m_T(W)$
- Fit in whole range, extrapolation to selected events($m_T(W)>50$ GeV)

Non-QCD: MC

QCD: non-iso μ ($I_{rel}>0.12$): data

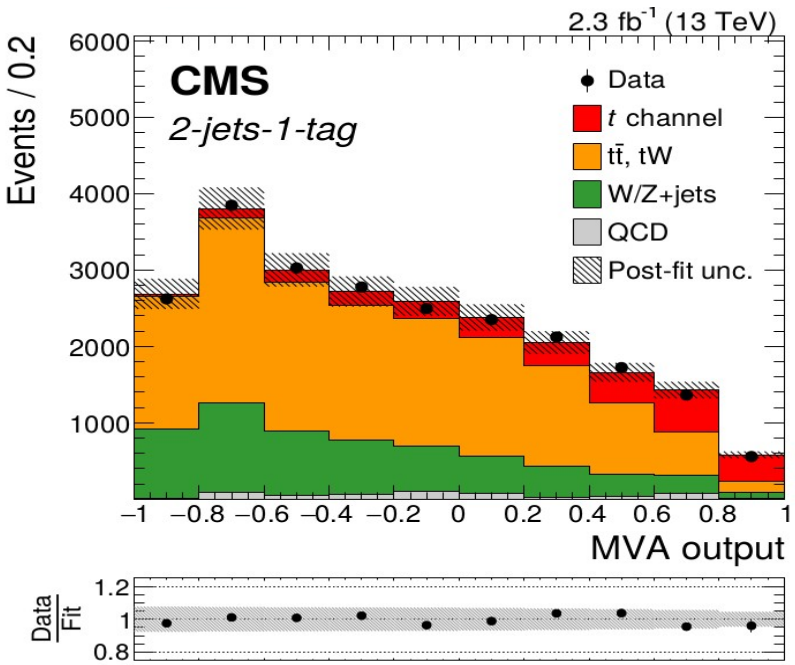
(non-QCD subtraction:MC)

Signal discrimination

artificial neural network is trained in 2j1t

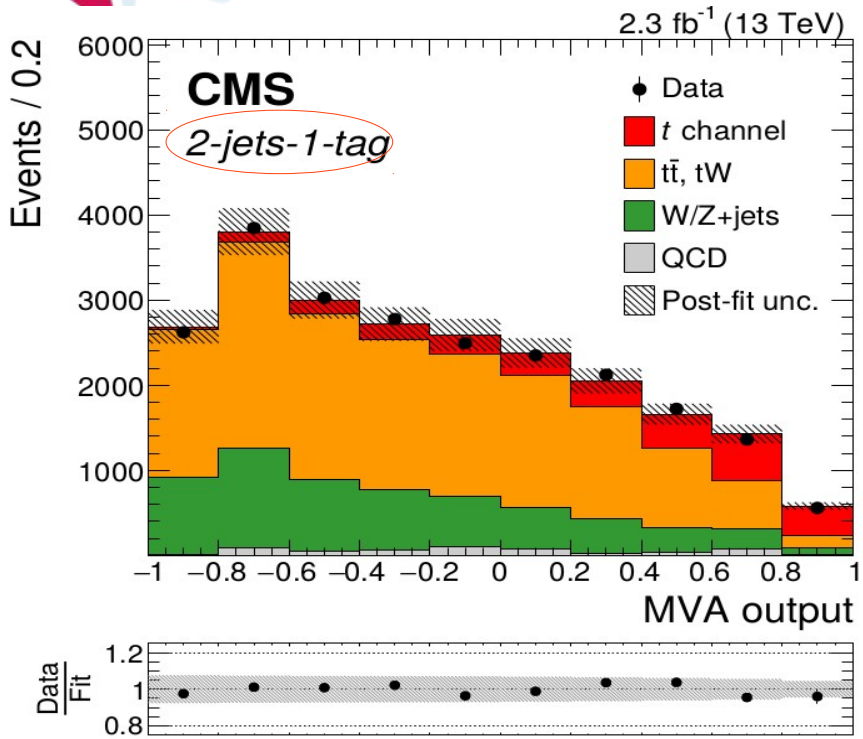
Important inputs:

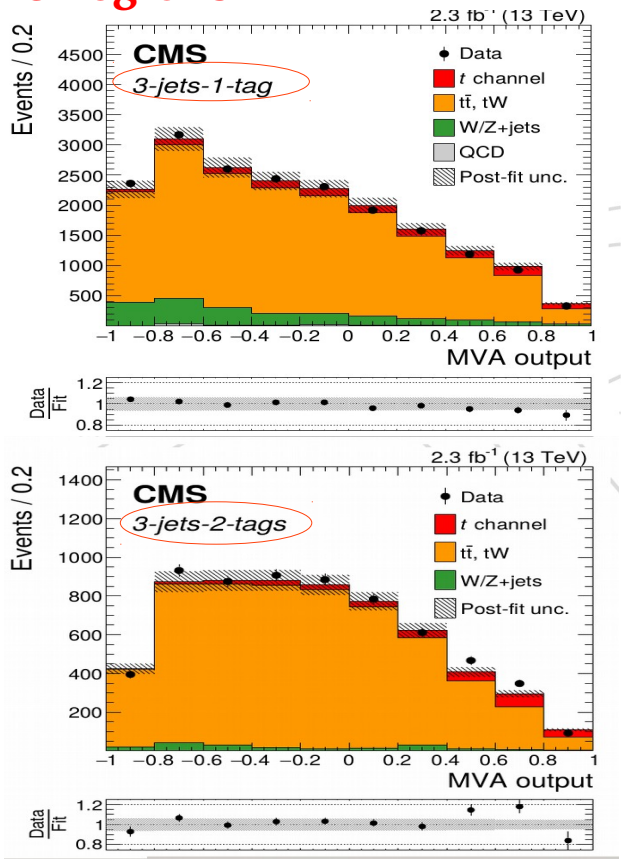
light jet$|\eta|$, reconstructed top mass



t-channel Inclusive Cross Section, TOP-16-003 (Paper in prep.)

Analysis Strategy:simultaneous fit in 3 regions





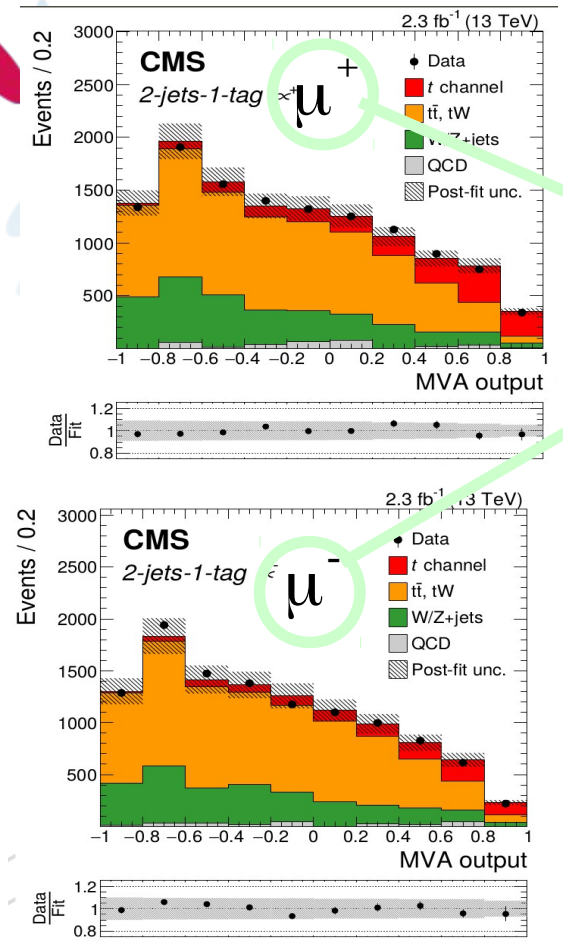
$$\sigma_{(t+\bar{t})} = 232 \pm 13\,(stat) \pm 12\,(\exp) \pm 26\,(theo) \pm 6\,(lumi) = 232 \pm 31\ pb$$

$$\sigma_{(t+\bar{t})} = 232 \pm 6\%\,(stat) \pm 5\%\,(\exp) \pm 11\%\,(theo) \pm 3\%\,(lumi) = 232 \pm 13\%\ pb$$

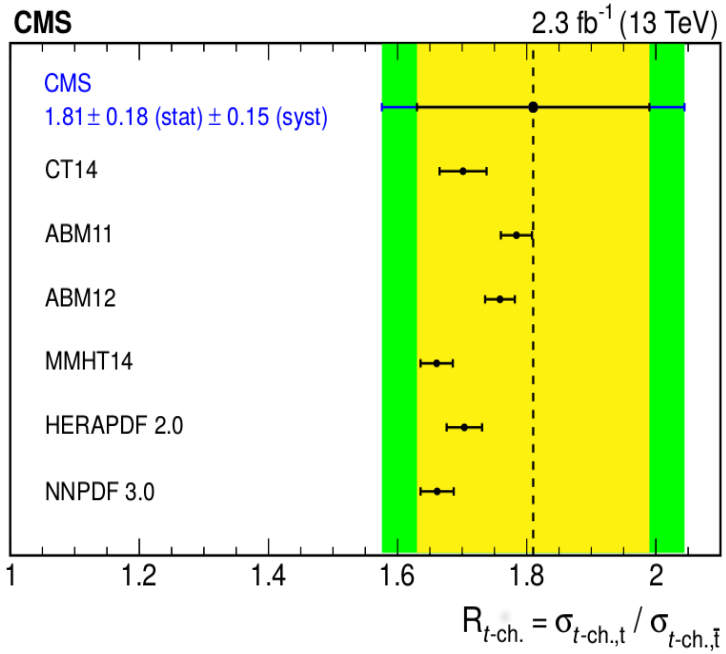
Mostly signal modeling:aMC@NLO ↔ Powheg

$$\sigma^{NNLL}_{t-channel} = 217^{+7}_{-5}\,(scale) \pm 6\,(PDF + \alpha_s)$$

t-channel Inclusive Cross Section, TOP-16-003 (Paper in prep.)



$$R_{t-ch.} = \sigma_{t-ch,t} / \sigma_{t-ch.,\bar{t}}$$



$\sigma_{t\text{-ch.},\,t}$ and $R_{t\text{-ch.}}$ are parameters of fit.

CKM matrix element V_{tb} ($|V_{tb}| >> |V_{ts}| >> |V_{td}|$):

$$|f_{LV} V_{tb}| = 1.03 \pm 0.07(\exp) \pm 0.03(theo)$$

anomalous form factor

t-channel Fiducial Cross Section @ 8TeV, TOP-15-007

In a fiducial cross section measurement:

- It is measured only in fiducial volume(detector acceptance)
- No extrapolation to experimentally non-accessible region.
- Factorize the corrections for detector response from those for acceptance
- Easier verification of theory (generator modeling) with data
- Very close criteria to detector level applied on particle level

Object	Kinematic cuts at detector level	Cuts at particle level	number required
Tight Muon	$p_T > 26$, $\|\eta\| < 2.1$, $I_{rel} < 0.12$	$p_T > 30$, $\|\eta\| < 2.4$	exactly 1 (or 1 Ele)
Tight Electron	$E_T > 30$, $\|\eta\| < 2.4$,$I_{rel} < 0.1$	$p_T > 30$, $\|\eta\| < 2.4$	exactly 1 (or 1 Mu)
Veto Muon	$p_T > 10$, $\|\eta\| < 2.4$, $I_{rel} < 0.2$	-	0
Veto Electron	$E_T > 20$, $\|\eta\| < 2.4$, $I_{rel} < 0.15$	-	0
Jets	$p_T > 40$, $\|\eta\| < 4.7$	$p_T > 40$, $\|\eta\| < 5.0$	exactly 2
B-tagging	1 jet is tagged	$\|\eta\| < 2.4$, b-hadron	exactly 1
m_T (muons)	$m_T > 50$	-	-
$\not{E}_T$ (electrons)	$\not{E}_T > 45$	-	-

At particle level

the definitions of objects follow closely the LHCTOPWG definitions for pseudo-top

t-channel Fiducial Cross Section @ 8TeV, Top-15-007

$$\sigma^{fid}_{t-ch} = \frac{N_{obs}}{\epsilon^{fid} \cdot L}$$

$$\epsilon^{fid} = \frac{N^{MC}_{rec}}{N^{MC}_{fid}}$$

Fit on eta distribution of light jet

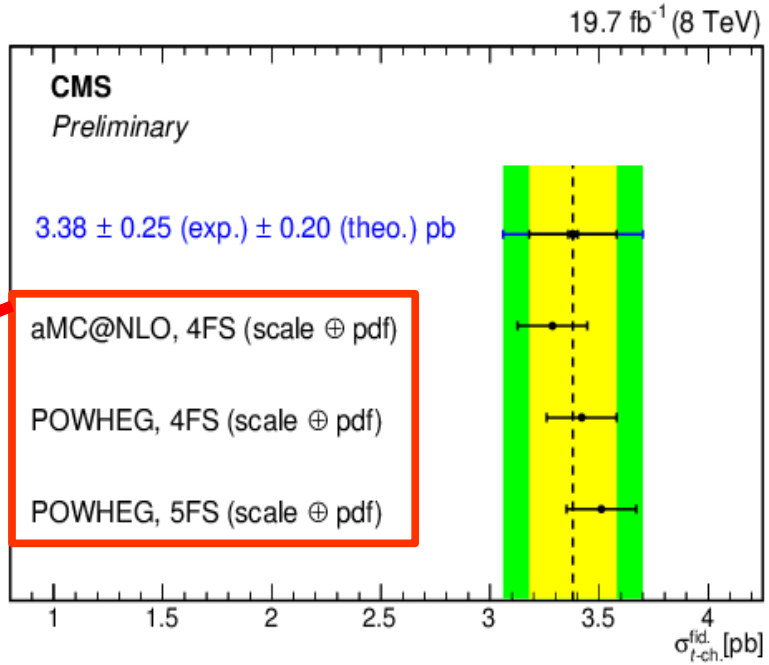
aMC@NLO, 4FS

$$\sigma^{fid}_{t-ch} = 3.83 \pm 0.25(\exp.) \pm 0.20(theo.)$$

$$\sigma^{fid}_{t-ch} = \sigma_{t-ch} \cdot A^{fid}$$

$$A^{fid} = \frac{\sigma^{fid,MC}_{t-ch}}{\sigma^{MC}_{t-ch}}$$

$$\sigma^{obs}_{t-ch} = 87.2 \pm 6.5(\exp.) \pm 2.2(theo.)$$



Predictions for $\sigma^{fid}_{t\text{-}ch}$:

- common $\sigma_{t\text{-}ch}$ (5FS with HATHOR)
- different A^{fid} for different generators .
- PDF and scale affect both $\sigma_{t\text{-}ch}$ and A_{fid}

Yellow band: experimental unc.
green band: total unc.

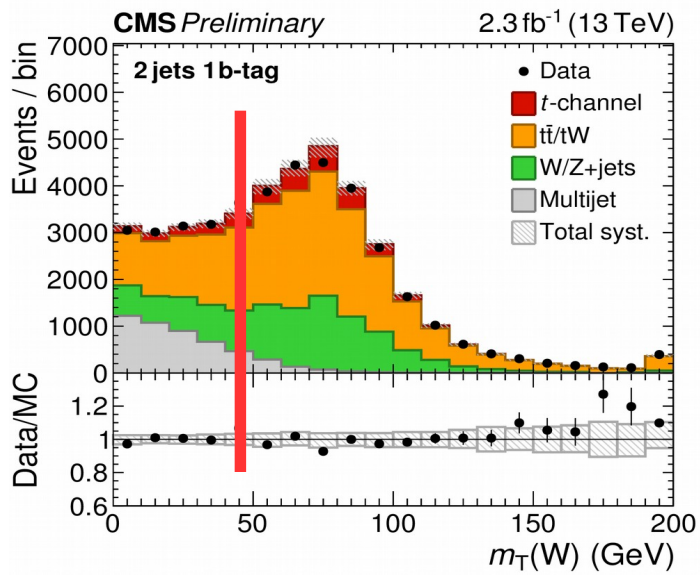
t-channel Differential Cross Section @ 13TeV, TOP-16-004

Signal yield is estimated in bins of top quark p_T and rapidity

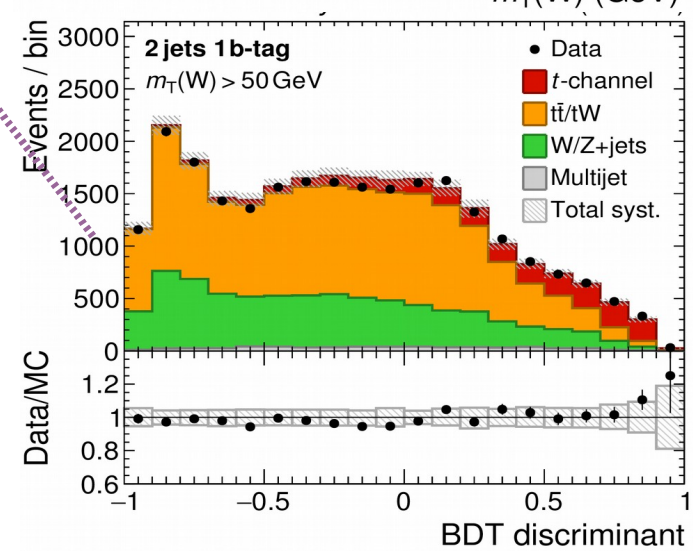
$2.3\,fb^{-1}$ data, same selections, signal and control regions to inclusive measurement

Data Driven multijet estimation:

- **Low MC statistic: shape from data with same selection but non-isolated lepton $I_{rel.} > 20\%$**
- **Using $m_T(W)$, as expect QCD at low $m_T(W)$**
- **Normalization: in fit simultaneously with signal extraction**



- **Well modeled observables in signal and control samples**
- **Low correlation to top p_T and y to avoid bias in data towards SM**
- $|\eta(j')|, m_{lb\nu}, \Delta R(b, j'), \Delta\eta(b, \mu)$
- **No selection on $m_T(W)$ in training**
  Trained in 2j1t, used it in all regions



t-channel Differential Cross Section @ 13TeV, TOP-16-004

Analysis strategy :

Simultaneous fit in 3 regions, inclusively or differentially

Fitted distribution

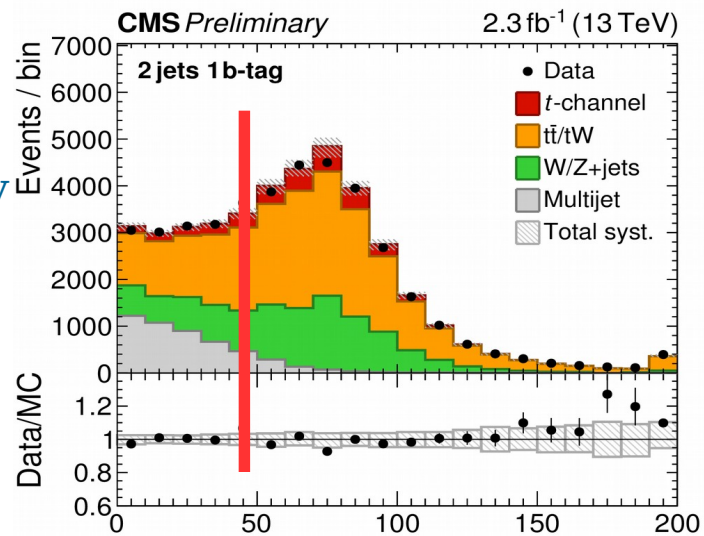
$m_T(W) < 50GeV$:

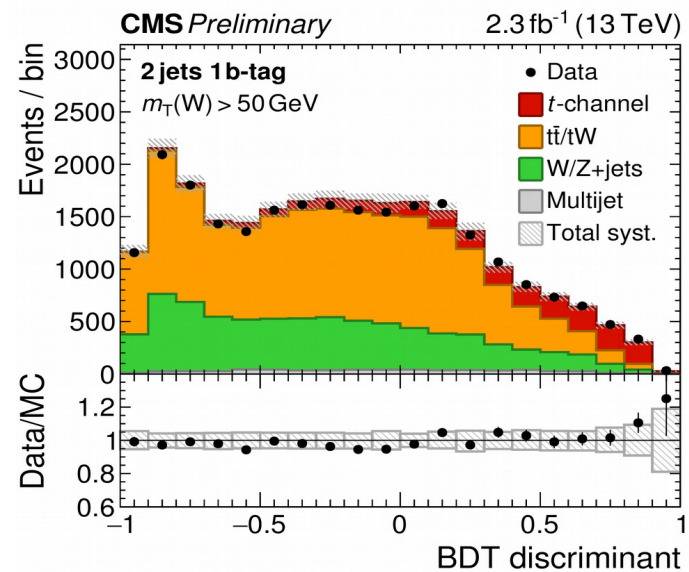
using **$m_T(W)$ distribution**, to mostly estimate QCD yield

QCD shape: from anti-iso data

$m_T(W) > 50GeV$:

using **BDT distribution**, to estimate signal and other backgrounds yield



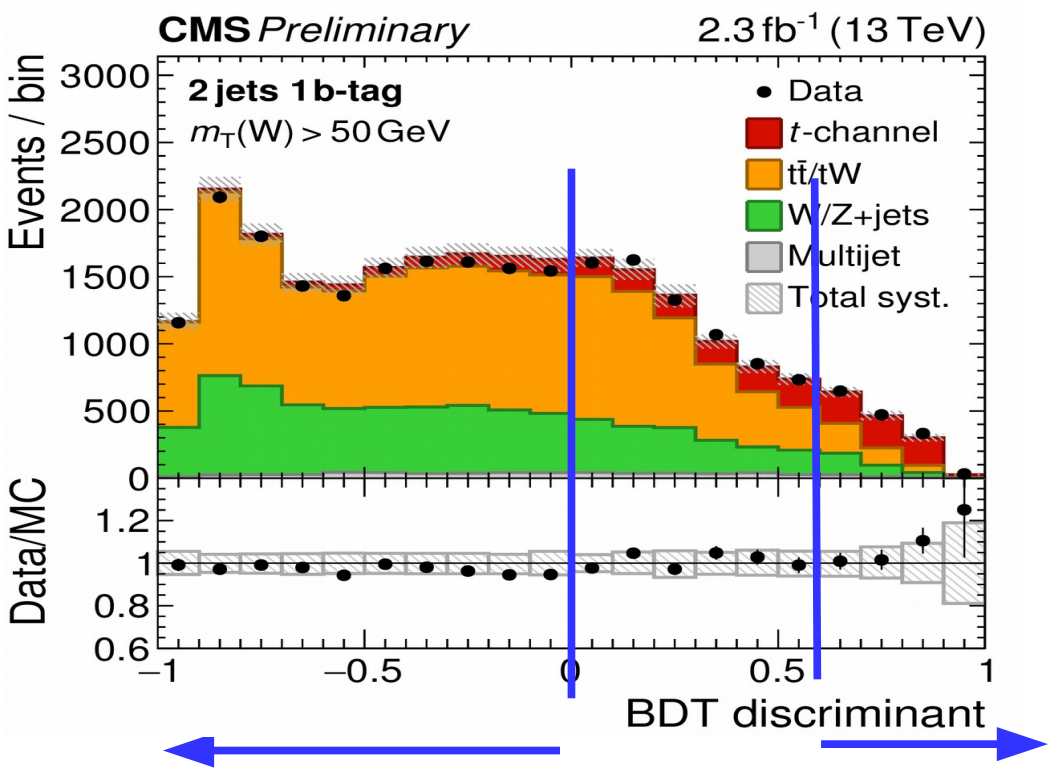


Simultaneous fit in 3 regions:

- enhances sensitivity to $t\bar{t}$,
- reduces it's anti-correlation with wjets norm. (90% -->33%)

t-channel Differential Cross Section @ 13TeV, TOP-16-004

Closer look on signal and backgrounds on unfolded variables distribution !



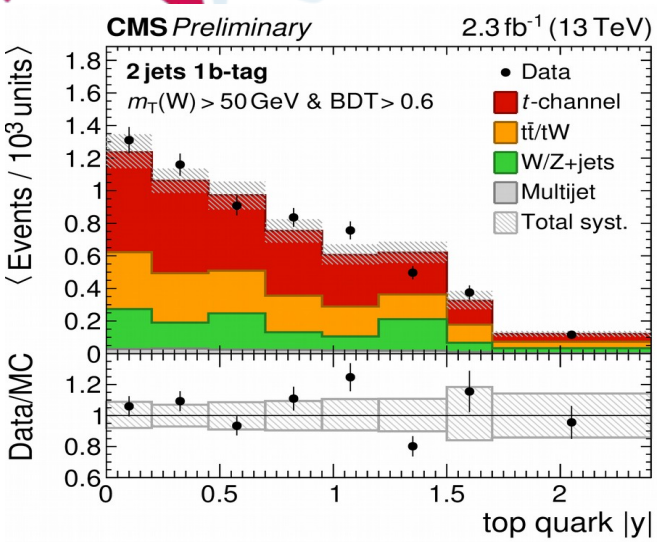
Signal depleted region

Signal enhanced region

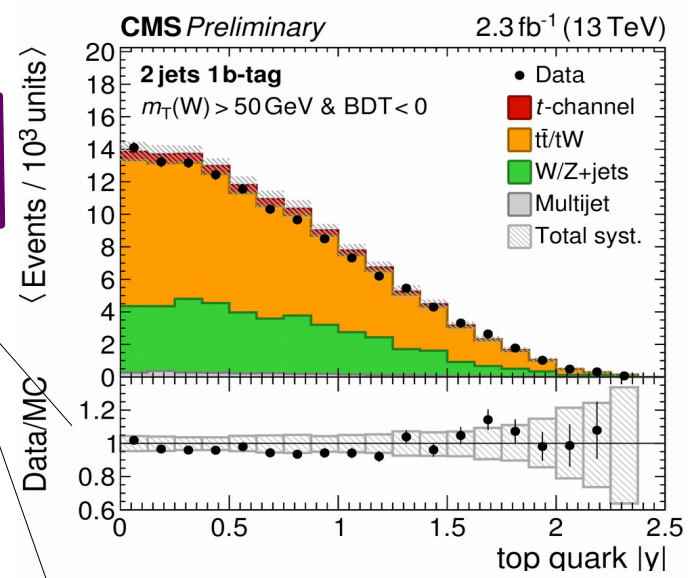
t-channel Differential Cross Section @ 13TeV, TOP-16-004

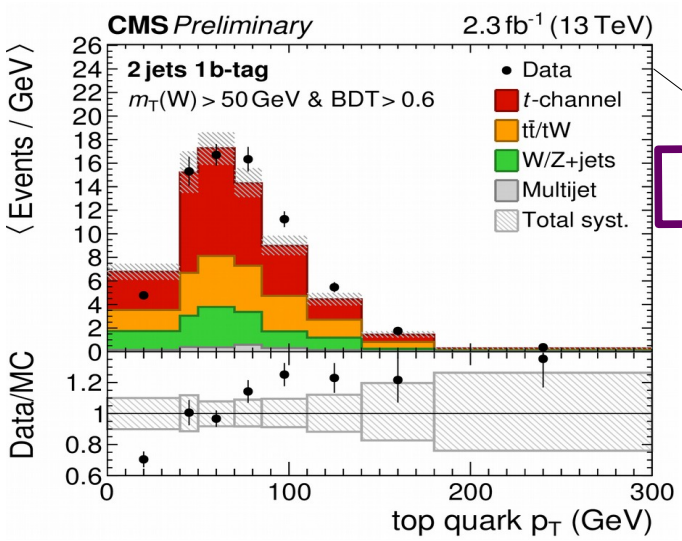
Signal enhanced region
$m_T(W) > 50GeV$, BDT>0.6

Signal depleted region
$m_T(W) > 50GeV$, BDT<0

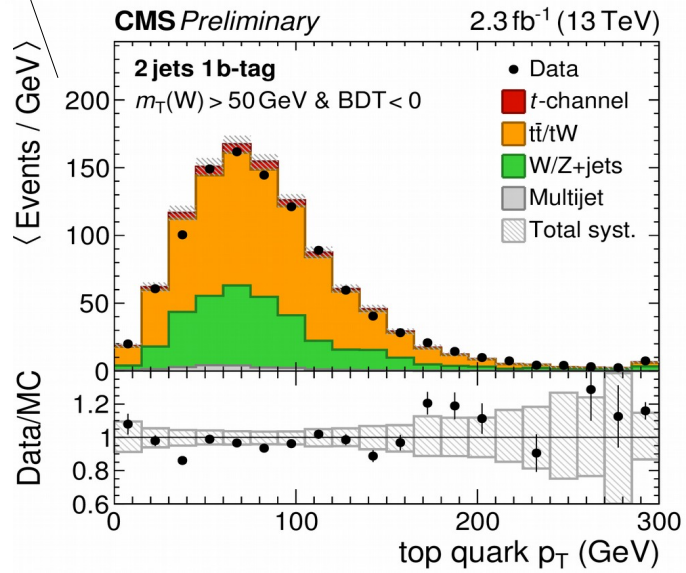


Good modeling Of Backgrounds!



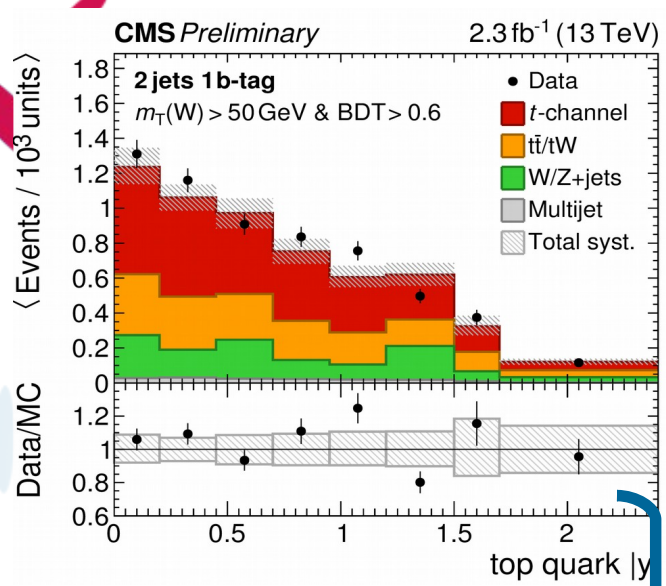


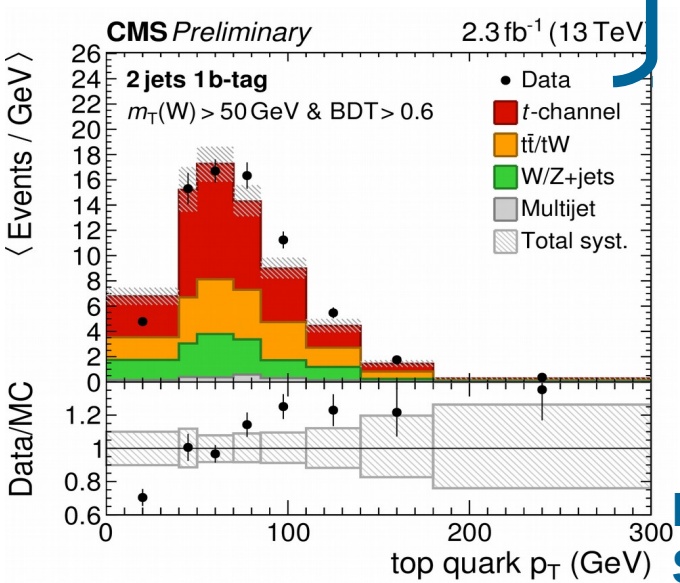
a harder spectrum in data

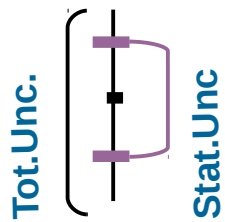


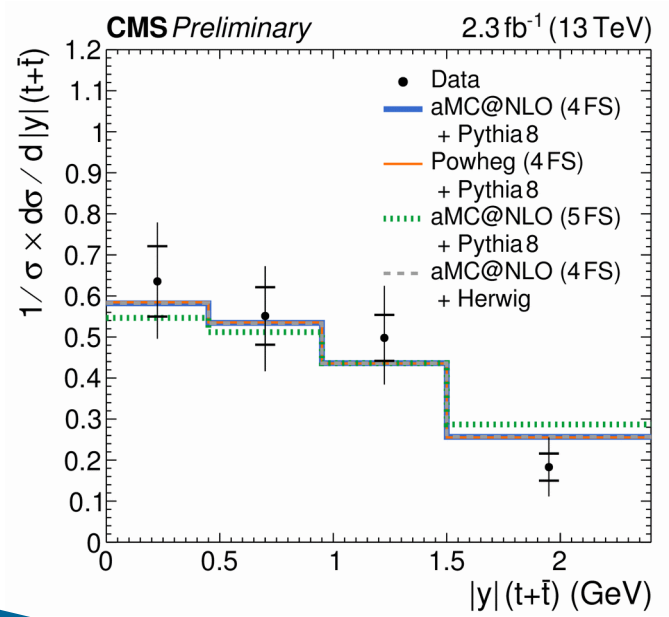
t-channel Differential Cross Section @ 13TeV, TOP-16-004

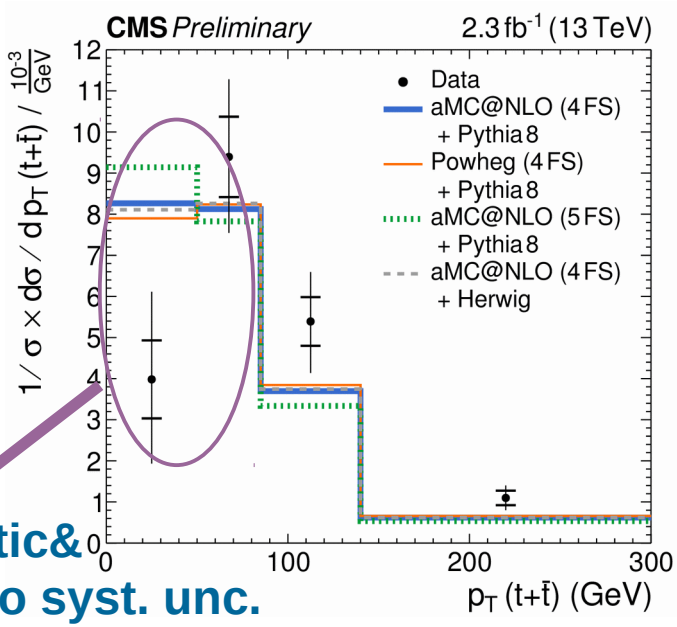
Signal enhanced region
$m_T(W) > 50GeV$, $BDT > 0.6$











Low statistic&
Sensitive to syst. unc.

Search for s-channel @ 7+8TeV, JHEP09(2016)027

8TeV, 19.7 fb^{-1}

Trigger:
Isolated muon(electron)

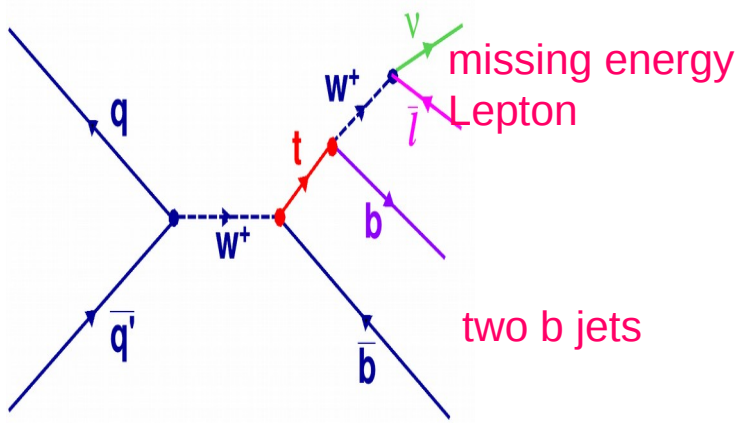
Exactly on lepton, Muon(Electron) :
p_T > 26(30) GeV, $|\eta|$< 2.1(2.5), I_{rel}<0.12(0.1)

Veto lepton:
p_T> 10 (20) GeV, $|\eta|$ < 2.5, I_{rel} < 0.2 (0.15) for μ(e)

Jet: anti-kT, R=0.5
$|\eta|$ < 4.7 and p_T> 40 GeV

Loose jet: (< 2 loose jet in signal region)
same as jet, but 20 < p_T < 40 GeV

b-tagging:
eff_b: 45%, $eff_{fake,light\ jet}$: 0.1%



2 jets, 2b-tagged jet (2-jets 2-tags)

2-jets 2-tags	Signal Region
2-jets 1-tag	t-ch. & wjets Region
3-jets 2-tags	$t\bar{t}$ Control Region
2-jets 0-tag	Wjets Control Region
	QCD shape validation

7TeV, 5.1 fb^{-1}

Trigger:
isolated muon
(in some runs: central b jet p_T>30 GeV)

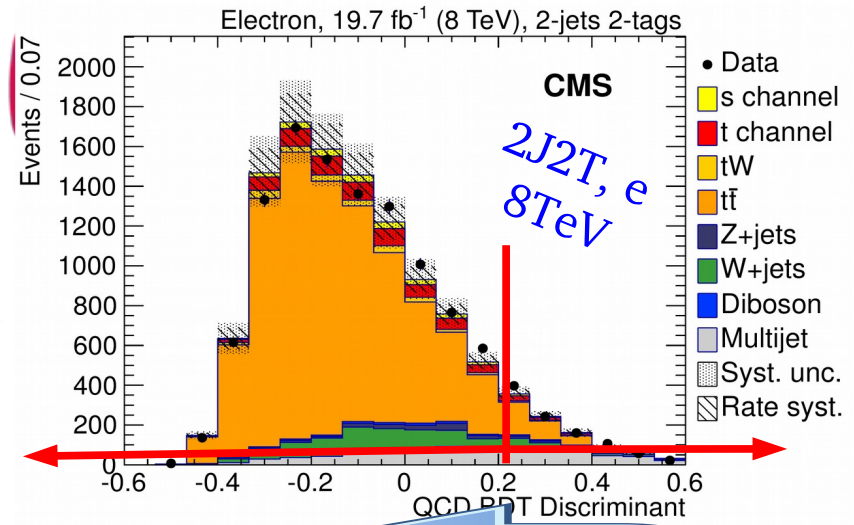
Muon:
p_T > 20 GeV, $|\eta|$ < 2.1, I_{rel} < 0.15

Veto lepton:
p_T> 10 GeV, $|\eta|$ < 2.5, I_{rel} < 0.2

Jet: anti-kT, R=0.5
$|\eta|$ < 4.7 and p_T> 40 GeV

b-tagging:
eff_b: 45%, $eff_{fake,light\ jet}$: 0.1%

Search for s-channel @ 7+8TeV, JHEP09(2016)027



extrapolated

Signal region

Used for signal extraction

QCD-enriched region

Used in anti-QCD BDT fit

Events eliminated from analysis

Data Driven QCD Estimation

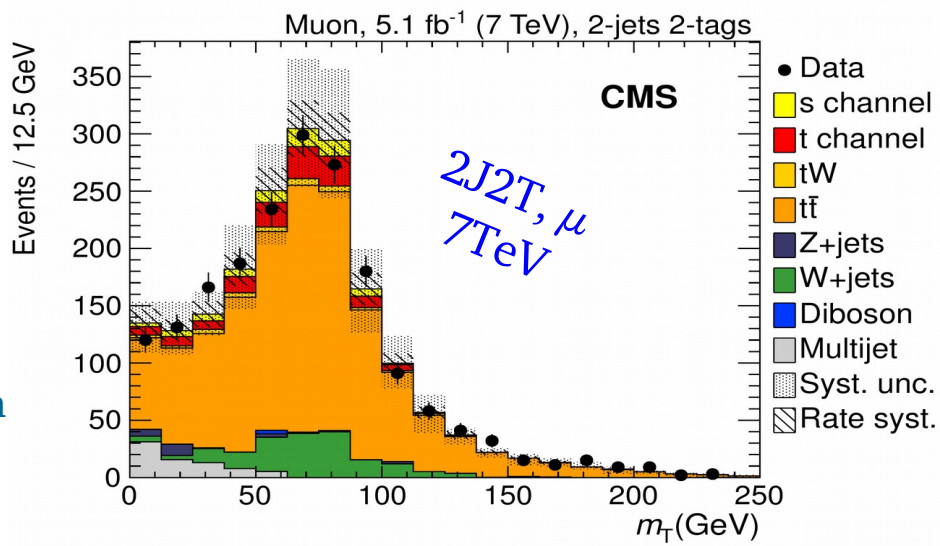
8TeV

- BDT is trained in signal/ control samples
- Separate QCD against tt and Wjet, single top
- QCD, taken from data with "anti-iso" selection
- Fit in QCD enriched region

Data Driven QCD Estimation

7TeV

- not enough statistics to train BDT
- ML fit on $m_T(W)$ distribution (2j2t, 3j2t)
- 2j1t: cut at 50GeV to reduce QCD contamination, QCD is taken from simulation



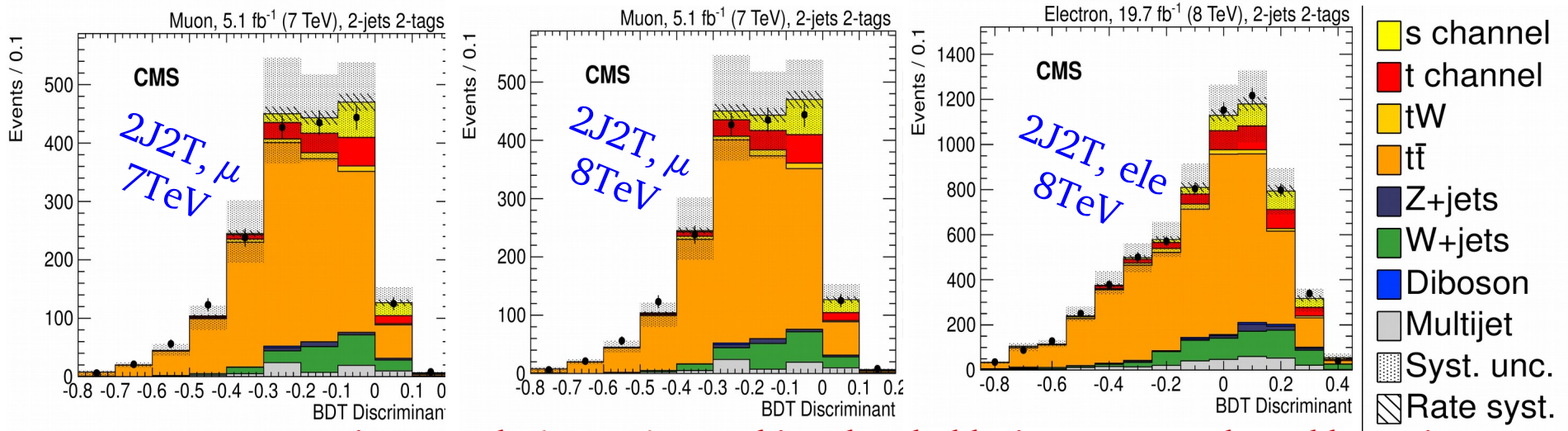
Search for s-channel @ 7+8TeV, JHEP09(2016)027

Signal extraction Strategy

For electron & muon at 7 and 8TeV, BDTs trained in 2J2T, 2J1T and 3J2T

- In 2J2T: s-channel vs rest
- In 3J2T: $t\bar{t}$ vs rest
- In 2J1T: Wjets vs rest

Simultaneous fit in signal and control sample



Important Uncertainty : Scale (μ_F, μ_R), matching thresholds, jet energy scale and b tagging

	Exp. Significance	Obs. Significance
8TeV, muon+electron	0.8	2.3
7 TeV, muon	0.5	0.9
7 + 8 TeV	1.1	2.5

	Exp. UL	Obs. UL
8 TeV, muon+electron	20.5 [13.4, 26.7] pb	28.8 pb
7 TeV, muon	25.4 [19.0, 36.6] pb	31.4 pb
7 + 8 TeV (UL on β)	3.1 [2.1, 4.0]	4.7

Search for SM tZq Process @ 8TeV, TOP-12-039

For FCNC tZq, see talks by I. Parijs & J. Espinosa

8TeV, 19.7 fb^{-1}

Trigger:
presence of two lepton with p_T>(17)8 GeV

Exactly three leptons from different flavors, Mu(Ele) :
p_T > 20GeV, $|\eta|$ < 2.4(2.5), I_{rel} < 0.12(0.15)

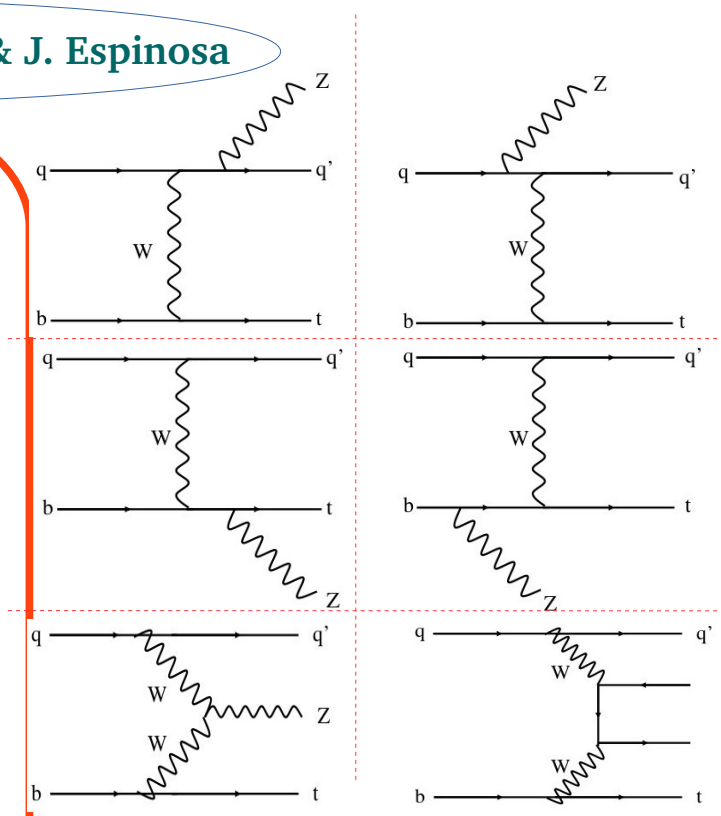
Two same flavor opposite charged leptons: 76<m_{ll}<106

Veto lepton:
Same kinematic, looser identification

Jet: anti-kT, R=0.5
$|\eta|$ < 4.5 and p_T> 30 GeV, reject jet if it's close to leptons(ΔR<0.5)

b-tagging:
loose WP, eff_b: 80%, $eff_{fake,light\ jet}$: 10%

$m_T(W)$>10GeV (optimized base on exp. significance)



Z reconstructed from

- OS SF leptons ($ee\mu$, $\mu\mu e$)
- OS SF lepton with closest mass to Z mass (eee, $\mu\mu\mu$)

At least two jets and at least one b-jet: signal region
One or two jet, veto b-jet: background region(DY and WZ)

Search for SM tZq Process @ 8TeV, TOP-12-039

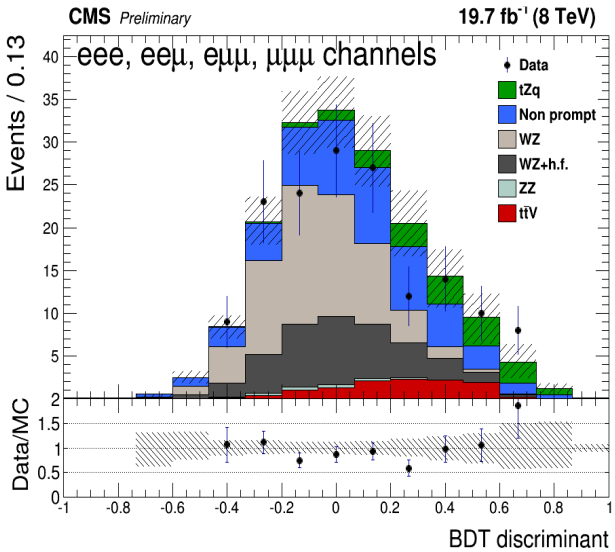
Analysis Strategy:

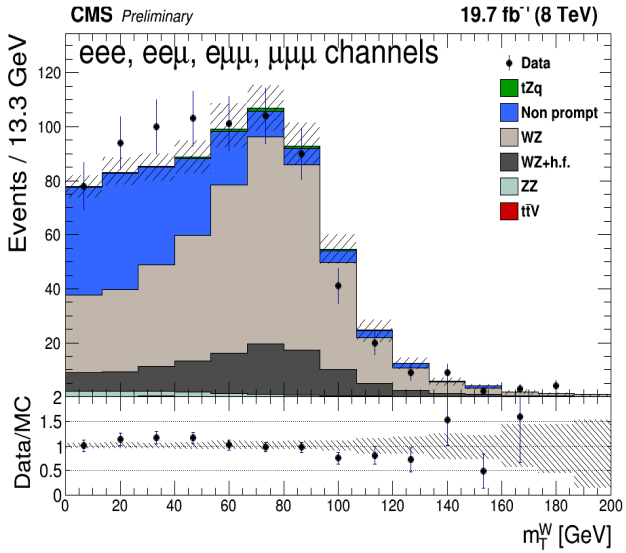
Background estimation: from simulation with 2 exceptions:

- non-prompt lepton ($t\bar{t}$ and DY) and WZ+jet (dominant background)
- estimated from data by a fit on **$m_T(W)$ distribution** in background sample
- Non prompt background template from non-isolated sample
- WZ+heavy flavor jet and WZ+light jet get free parameters in fit

Signal Separation: BDT is trained to separate SM tZq from $t\bar{t}Z$ and WZ

Simultaneous fit on BDT($m_T(W)$) distribution in signal (background) region





Confirmed by a cut and count measurement

Observed(expected) significances: 2.4 (1.8)σ

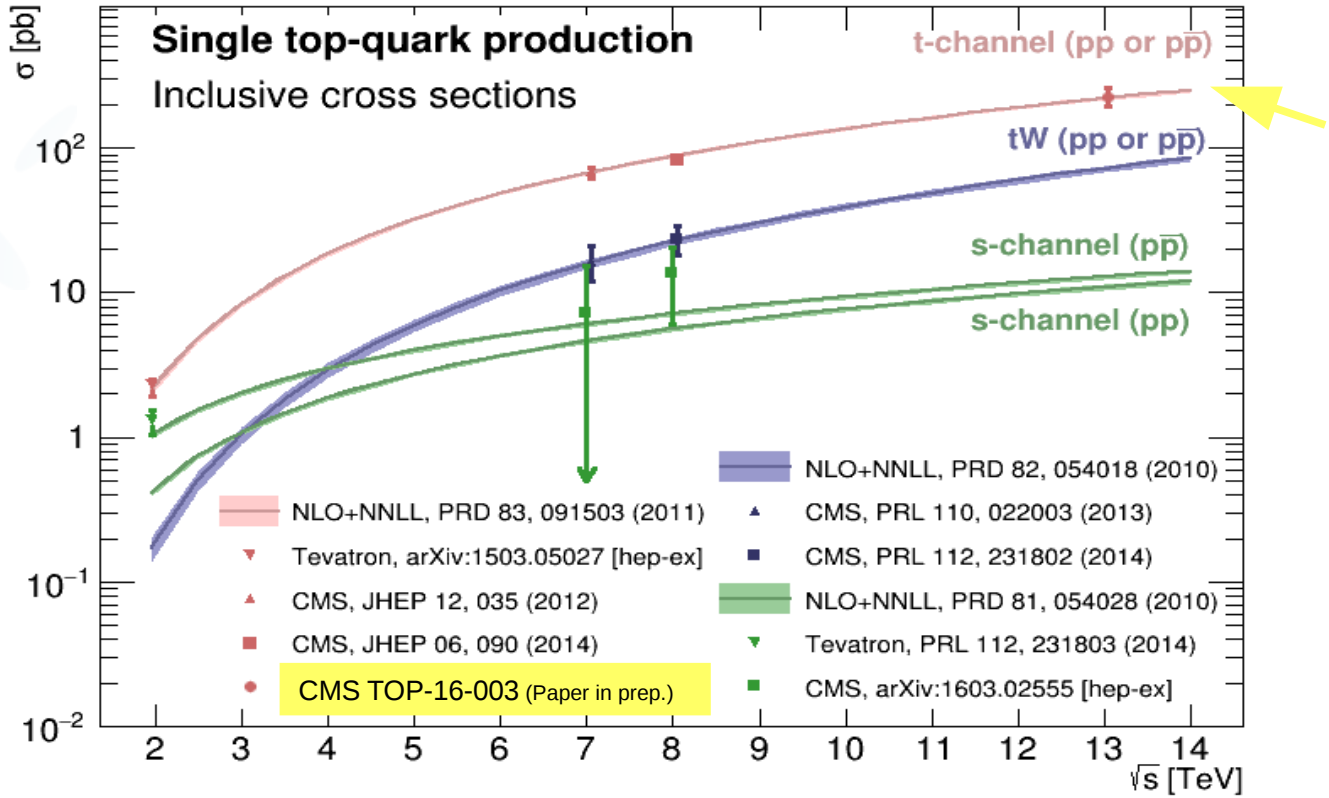
Measured upper limit at 95% CL. : 21 fb

Measured cross section: $\sigma_{tZq} = 10.^{+8}_{-7}$ fb

$$\sigma_{tZq,SM} = 8.2^{+.59}_{-0.03}(scale)\,fb$$

Summary

CMS has measured different production modes of single Top quark in at 7, 8 and 13TeV center of mass energies.



more precise measurements @13 TeV are coming!
Stay tuned !

Back up

t-channel Inclusive Cross Section,TOP-16-003 (Paper in prep.)

Neural network inputs

Rank	Variable	Description
1	light quark $\lvert\eta\rvert$	Absolute value of the pseudorapidity of the light-quark jet
2	top quark mass	Invariant mass of the top quark reconstructed from muon, neutrino, and b-tagged jet
3	dijet mass	Invariant mass of the two selected jets
4	transverse W boson mass	Transverse mass of the W boson, calculated from the muon momentum and the $\vec{p\!\!\!/}_{\mathrm{T}}$
5	jet-p_{T} sum	Scalar sum of the transverse momenta of the two jets
6	$\cos\theta^*$	Cosine of the angle between the muon and the light-quark jet in the rest frame of the top quark
7	hardest jet mass	Invariant mass of the jet with the largest transverse momentum
8	ΔR (light quark, b quark)	Difference in R between the light-quark jet and the b-tagged jet.
9	light quark p_{T}	Transverse momentum of the light-quark jet
10	light quark mass	Invariant mass of the light-quark jet
11	W boson $\lvert\eta\rvert$	Absolute value of the pseudorapidity of the reconstructed W boson

Scale factor for each process from the fit

Process	Scale factor
Signal, t channel	1.10±0.08
Top quark background ($t\bar{t}$ and tW)	0.98±0.02
W+jets and Z+jets	1.08±0.09
QCD multijet	0.84±0.29
$R_{t\text{-ch.}}$	1.81±0.19

t-channel Inclusive Cross Section,TOP-16-003 (Paper in prep.)

Relative impact of the systematic uncertainties with respect to the observed cross section value

Uncertainty source	$\Delta\sigma_{t\text{-ch.},t+\bar{t}}/\sigma^{obs}_{t\text{-ch.},t+\bar{t}}$	$\Delta\sigma_{t\text{-ch.},t}/\sigma^{obs}_{t\text{-ch.},t}$	$\Delta\sigma_{t\text{-ch.},\bar{t}}/\sigma^{obs}_{t\text{-ch.},\bar{t}}$	$\Delta R_{t\text{-ch.}}/R_{t\text{-ch.}}$
Statistical uncert.	±5.5%	±5.3%	±11.5%	±9.7%
Profiled exp. uncert.	±5.2%	±5.7%	±4.9%	±3.3%
Total fit uncert.	±7.6%	±7.8%	±12.5%	±10.3%
Integrated luminosity	±2.7%	±2.7%	±2.7%	-
Signal modelling	±6.9%	±8.2%	±8.5%	±5.3%
$t\bar{t}$ modelling	±3.9%	±4.3%	±4.5%	±4.0%
W+jets modelling	−1.8/+2.1%	−1.6/+2.3%	−2.5/+2.3%	−1.7/+2.0%
μ_R/μ_F scale t-channel	−4.6/+6.1%	−5.7/+5.2%	−7.2/+5.1%	−0.7/+1.2%
μ_R/μ_F scale $t\bar{t}$	−3.5/+2.9%	−3.5/+4.1%	−4.7/+3.1%	−1.1/+1.0%
μ_R/μ_F scale tW	−0.3/+0.5%	−0.6/+0.8%	−1.1/+0.7%	−0.2/+0.1%
μ_R/μ_F scale W+jets	−2.9/+3.7%	−3.5/+3.0%	−4.9/+3.8%	−1.2/+0.9%
PDF uncert.	−1.5/+1.9%	−2.1/+1.6%	−1.8/+2.1%	−2.2/+2.5%
Top quark p_T modelling	±0.1%	±0.2%	±0.2%	±0.1%
Total theory uncert.	−10.7/+11.1%	−12.2/+12.1%	−13.6/+12.9%	±7.5%
Total uncert.	−13.4/+13.7%	±14.7%	−18.7/+18.2%	±12.7%

Uncertainty source	$\Delta\sigma_{t\text{-ch.},t+\bar{t}}/\sigma^{obs}_{t\text{-ch.},t+\bar{t}}$	$\Delta\sigma_{t\text{-ch.},t}/\sigma^{obs}_{t\text{-ch.},t}$	$\Delta\sigma_{t\text{-ch.},\bar{t}}/\sigma^{obs}_{t\text{-ch.},\bar{t}}$	$\Delta R_{t\text{-ch.}}/R_{t\text{-ch.}}$
MC samples size	±3.4%	±4.1%	±3.8%	±3.2%
JES	±4.1%	±4.7%	±3.5%	±2.1%
JER	±1.7%	±1.2%	±2.4%	±0.6%
b tagging efficiency	±1.9%	±2.0%	±1.8%	±1.4%
Mistag probability	±0.9%	±0.6%	±0.8%	±0.5%
Muon reco./trigger	±2.0%	±2.3%	±1.9%	±1.8%

Exp. uncertainties included in fit (profiled unc.)

t-channel Inclusive Cross Section,TOP-16-003 (Paper in prep.)

Process	μ^+	μ^-
Top quark ($t\bar{t}$ and tW)	7048±13	7056±13
W+jets and Z+jets	2837±83	2564±77
QCD multijet	302±151	262±131
Single top quark t-channel	1539±13	977±10
Total expected	11726±173	10859±153
Data	11877	11017

Event yields for the main processes in the 2-jets-1-tag sample

MC based except QCD

Stat. Unc. Only, QCD : 50% to cover syst. in estimation.

Wjets with NLO/LO SF

t-channel fiducial Cross Section @ 8TeV,Top-15-007

Object	Kinematic cuts at detector level	Cuts at particle level	number required
Tight Muon	$p_T > 26$, $\|\eta\| < 2.1$, $I_{rel} < 0.12$	$p_T > 30$, $\|\eta\| < 2.4$	exactly 1 (or 1 Ele)
Tight Electron	$E_T > 30$, $\|\eta\| < 2.4$,$I_{rel} < 0.1$	$p_T > 30$, $\|\eta\| < 2.4$	exactly 1 (or 1 Mu)
Veto Muon	$p_T > 10$, $\|\eta\| < 2.4$, $I_{rel} < 0.2$	-	0
Veto Electron	$E_T > 20$, $\|\eta\| < 2.4$, $I_{rel} < 0.15$	-	0
Jets	$p_T > 40$, $\|\eta\| < 4.7$	$p_T > 40$, $\|\eta\| < 5.0$	exactly 2
B-tagging	1 jet is tagged	$\|\eta\| < 2.4$, b-hadron	exactly 1
m_T (muons)	$m_T > 50$	-	-
$\not{E}_T$ (electrons)	$\not{E}_T > 45$	-	-

At particle level : stable particles: $c\,\tau > 10\,mm$

- Prompt lepton: not from hadron decays ,radiations in a cone 0.1 are recovered for leptons(dressed)
- Jets: Clustering around stable particles excluding prompt leptons/photons
- Bjets: by rescale or ghost definition:
  non-resonant b-hadrons not decaying to other hardons are identified as stable particle
  rescale momentum to very small value, no effect on reconstructed jets
  These jets are identified as b jet

TW channel observation @ 8TeV, PRL 112 (2014) 231802

8TeV, 12.2 fb^{-1}

Trigger:
presence of two lepton with p_T>17 & 8 GeV

Two opposite charged isolated lepton , Muon(Electron) :
p_T > 20 GeV, |η| < 2.1(2.5), identification criteria

Veto lepton:
p_T> 10 GeV, loose criteria

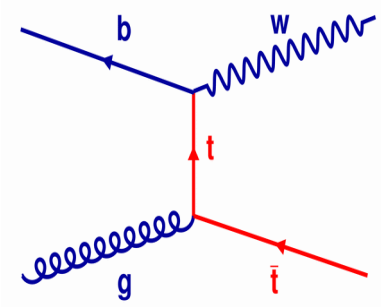
Dilepton mass:
m_{ll} > 20 , out of 80<m_{ll}<110

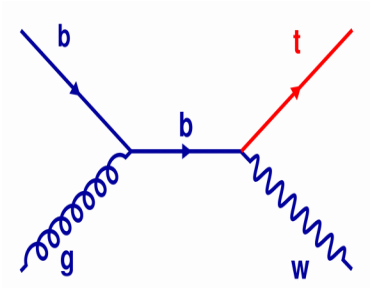
Jet: anti-kT, R=0.5
|η| < 2.4 and p_T> 30 GeV

Loose jet (central loose jet) :
Fail jet |η|,p_T selection, |η| < 4.9 (2.4) and p_T> 20 GeV,

b-tagging:
Medium WP, eff_b: 70%, $eff_{fake,light\ jet}$: 1%

$E_{T,miss}$ >50GeV





1 jets, 1b-taged jet (1j1t)

1-jets–1-tag Signal Region

2-jets–1-tag
2-jets–2-tag } $t\bar{t}$ Control Region

	1j1t	2j1t	2j2t
tW	1500±20±130	790±20±80	220±10±30
$t\bar{t}$	7090±60±900	12 910±80±1320	7650±60±1020
Z/γ^*, other	670±30±90	370±30±60	36±7±12
Total simulation	9260±70±1040	14 070±90±1410	7910±70±1020
Data	9353	13 479	7615

statistical (first) and systematic (second) uncertaintie

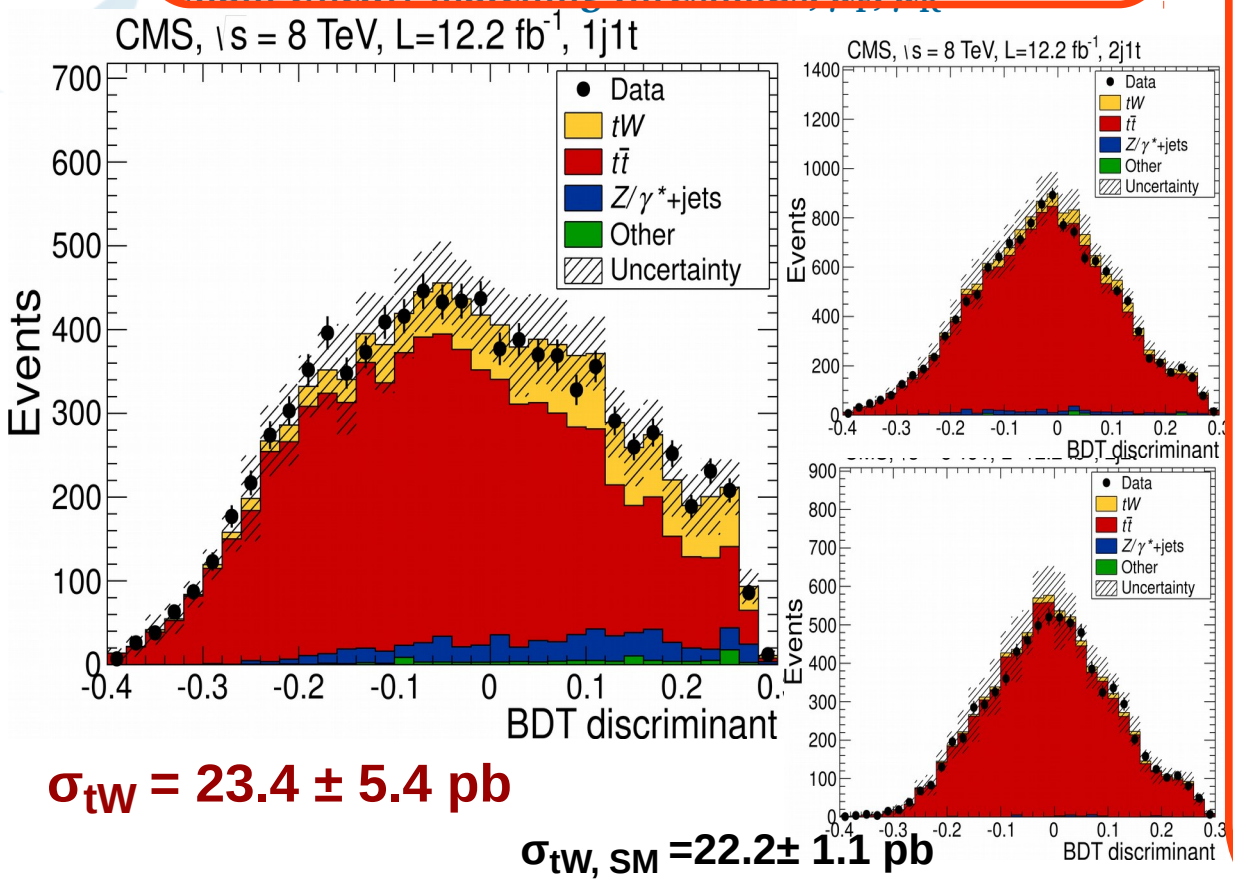
Main background : $t\bar{t}$, Z/γ^* + *jets*

Re-weighted, SF from Z mass window

TW channel observation @ 8TeV, PRL 112 (2014) 231802

BDT is trained in each region.
Most powerful observables: loose jet related ones!

profile likelihood fit performed to extract signal
Main Unc.: $t\bar{t}$ matching thresholds, μ_F, μ_R



σ_{tW} = 23.4 ± 5.4 pb

$\sigma_{tW,\,SM}$ =22.2± 1.1 pb

Significance obs.(exp.) = 6.1 (5.4) σ

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

Cobmination with ATLAS

σ_{tW}=23.1 ± 3.6pb

Source	Uncertainty (%)	Uncertainty (pb)
Data statistics	4.7	1.1
Simulation statistics	0.8	0.2
Luminosity	3.6	0.8
Theory modelling	11.8	2.7
Background normalization	2.2	0.5
Jets	6.2	1.4
Detector modelling	4.9	1.1
Total systematics (excl. lumi)	14.4	3.3
Total systematics (incl. lumi)	14.8	3.4
Total uncertainty	15.6	3.6

TW channel observation @ 8TeV, PRL 112 (2014) 231802

Systematic Uncertainty	$\Delta\sigma$ (pb)	$\frac{\Delta\sigma}{\sigma}$
ME/PS matching thresholds	3.25	14%
Q^2 scale	2.68	11%
Top quark mass	2.28	10%
Statistical	2.13	9%
Luminosity	1.13	5%
JES	0.91	4%
$t\bar{t}$ cross section	0.87	4%
Z+jet data/MC scale factor	0.56	2%
tW DR/DS scheme	0.45	2%
PDF	0.33	1%
Lepton identification	0.31	1%
JER	0.27	1%
B-tagging data/MC scale factor	0.20	$< 1\%$
$t\bar{t}$ Spin Correlations	0.12	$< 1\%$
Top Pt Reweighting	0.12	$< 1\%$
Event pile up	0.11	$< 1\%$
$E_{\mathrm{T}}^{\mathrm{miss}}$ modeling	0.07	$< 1\%$
Lepton energy scale	0.02	$< 1\%$
Total	5.58	24%

TW channel observation @ 8TeV, PRL 112 (2014) 231802

Variable Description
Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 4.9$
Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 2.4$
Number of loose jets, $p_T > 20$ GeV, b-tagged, $\|\eta\| < 2.4$
Vector sum of p_T of leptons, jet, and
Scalar sum of p_T of leptons, jet, and
p_T of the leading, tight, b-tagged jet
p_T of leading loose jet, defined as 0 for events with no loose jet present
Ratio of $p_{T,sys}$ to H_T for the event
Invariant mass of the combination of the leptons, jet, and
Centrality of jet and leptons
Ratio of scalar sum of p_T of the leptons to the H_T of full system
Vector sum of p_T of jet and leptons
Missing transverse energy in the event

Search for s-channel @ 7+8TeV,JHEP09(2016)027

$$\sigma_s = 7.1 \pm 8.1\,(\text{stat} + \text{syst})\,\text{pb}, \quad \text{muon channel, 7 TeV};$$
$$\sigma_s = 11.7 \pm 7.5\,(\text{stat} + \text{syst})\,\text{pb}, \quad \text{muon channel, 8 TeV};$$
$$\sigma_s = 16.8 \pm 9.1\,(\text{stat} + \text{syst})\,\text{pb}, \quad \text{electron channel, 8 TeV};$$
$$\sigma_s = 13.4 \pm 7.3\,(\text{stat} + \text{syst})\,\text{pb}, \quad \text{combined, 8 TeV}.$$

B=2.0 ± 0.9 combined

Channel	Observed UL	Expected UL—SM signal	Expected UL—no signal
μ, 7 TeV	31.4 pb	25.4 [19.0, 36.6] pb	20.2 pb
μ+e, 8 TeV	28.8 pb	20.5 [13.4, 26.7] pb	15.6 pb
7+8 TeV	4.7	3.1 [2.1, 4.0]	2.2

Search for s-channel @ 7+8TeV,JHEP09(2016)027

Source	Uncertainty (%)				
	μ, 7 TeV	μ, 8 TeV	e, 8 TeV	μ + e, 8 TeV	7+8 TeV
Statistical	34	15	14	10	11
$t\bar{t}$, single top quark rate	29	15	14	12	14
W/Z+jets, diboson rate	23	11	13	12	12
Multijet rate	9	3	5	2	2
Lepton efficiency	14	1	2	1	3
Hadronic trigger	5	—	—	—	1
Luminosity	10	5	6	4	6
JER & JES	66	39	29	34	18
b tagging & mistag	34	15	14	14	16
Pileup	6	11	7	9	7
Unclustered $\not{E}_T$	5	8	2	6	5
μ_R, μ_F scales	54	34	31	30	28
Matching thresholds	43	11	12	7	17
PDF	12	8	7	7	9
Top quark p_T reweighting	3	5	7	6	6
Total uncertainty	115	64	54	55	47

Search for s-channel @ 7+8TeV,JHEP09(2016)027

Lepton	Event category	Acceptance (%)	
		Multijet	s channel
μ	2-jets 1-tag	38	75
	2-jets 2-tags	50	92
	3-jets 2-tags	30	74
e	2-jets 1-tag	29	58
	2-jets 2-tags	60	92
	3-jets 2-tags	40	68

Process	μ, 7 TeV	μ, 8 TeV	e, 8 TeV
$t\bar{t}$	1380 ± 80	4960 ± 340	4290 ± 300
W+jets	150 ± 30	580 ± 110	620 ± 110
Z +jets	22 ± 7	160 ± 40	90 ± 30
Diboson	3 ± 3	59 ± 16	46 ± 13
Multijet	70 ± 20	130 ± 40	290 ± 60
tW	37 ± 6	149 ± 19	130 ± 16
t channel	135 ± 16	570 ± 50	420 ± 40
s channel	129 ± 5	452 ± 16	347 ± 12
Total MC	1920 ± 110	7060 ± 370	6240 ± 320
Data	1883	7023	6301