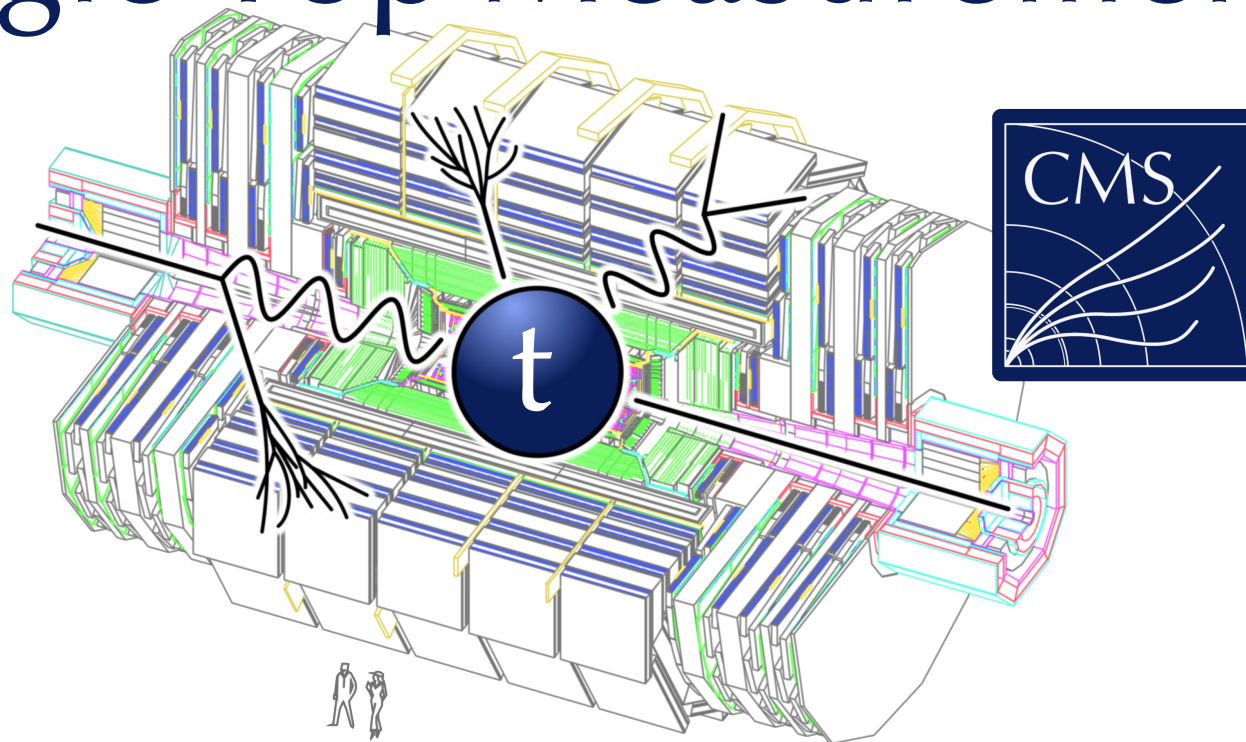


# Single Top Measurements



---

## Cross sections & Properties

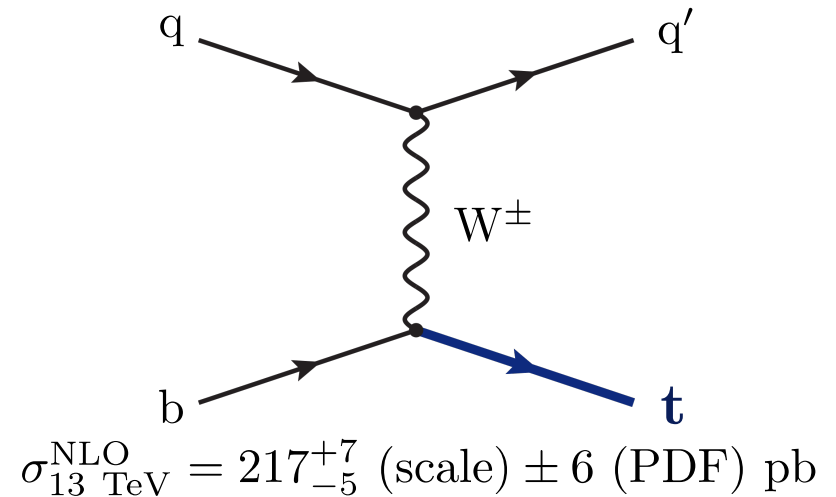
QCD@LHC  
2016

Matthias Komm

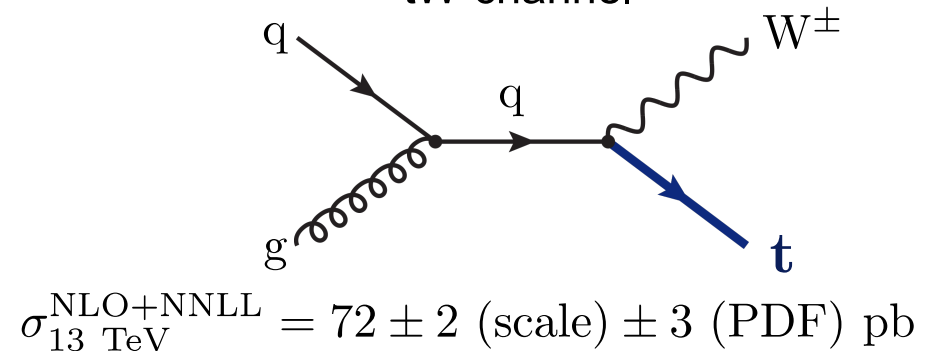
# Outline

- single top cross section measurements
  - inclusive t-channel cross section @ 13 TeV
  - differential t-channel cross section @ 13 TeV
  - s-channel cross section @ 7,8 TeV
  
- results on single top couplings
  - single top polarization @ 8 TeV
  - search for  $t + \gamma/Z$  production @ 8 TeV

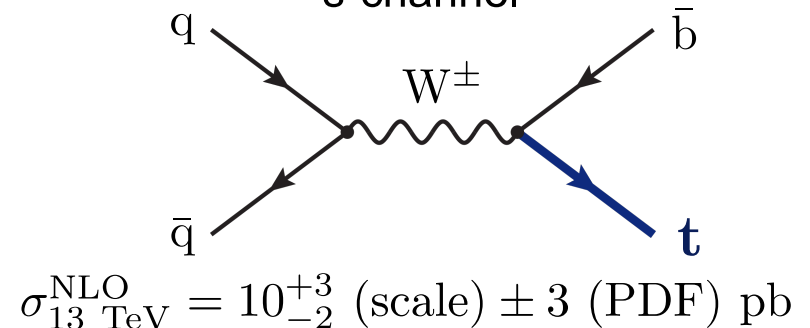
t-channel (dominant @ LHC)



tW-channel



s-channel

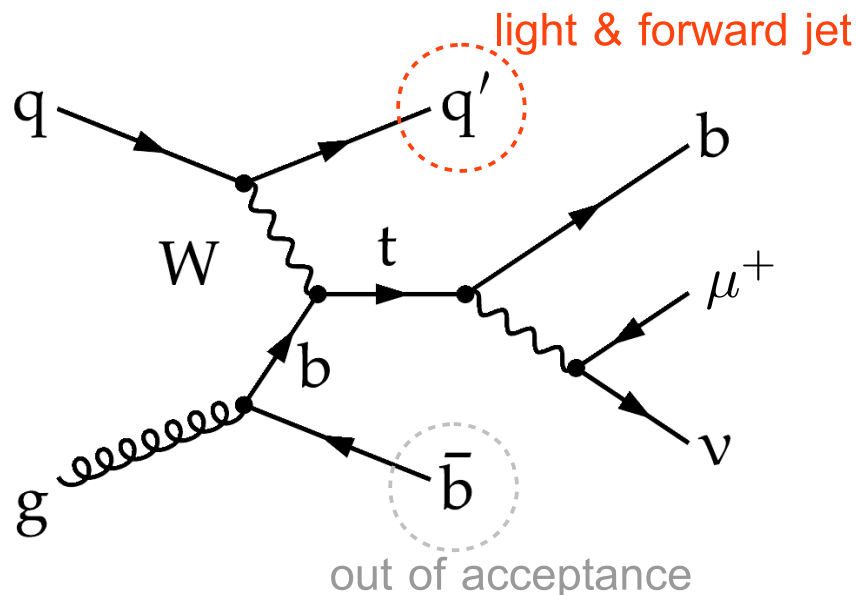


# Single top: cross section measurements

# t-channel cross section @ 13 TeV

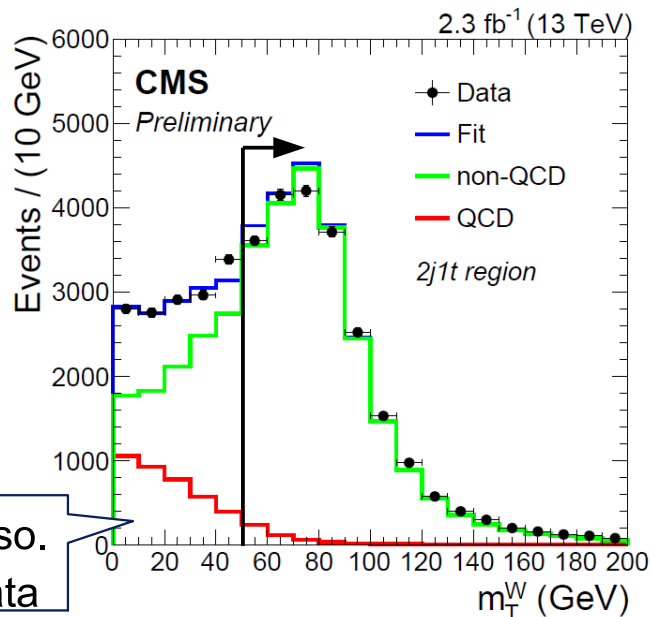
## ➤ event selection

- 1 isolated muon  
 $p_T > 22 \text{ GeV}$ ,  $|\eta| < 2.1$
- anti- $k_T$  jets ( $R = 0.4$ )  
 $p_T > 40 \text{ GeV}$ ,  $|\eta| < 4.7$
- MVA-based b-tagging  
 $\epsilon_b \approx 45\%$ ,  $\epsilon_{fake} \approx 0.1\%$
- reject multijet events from QCD  
 $m_T(W) > 50 \text{ GeV}$

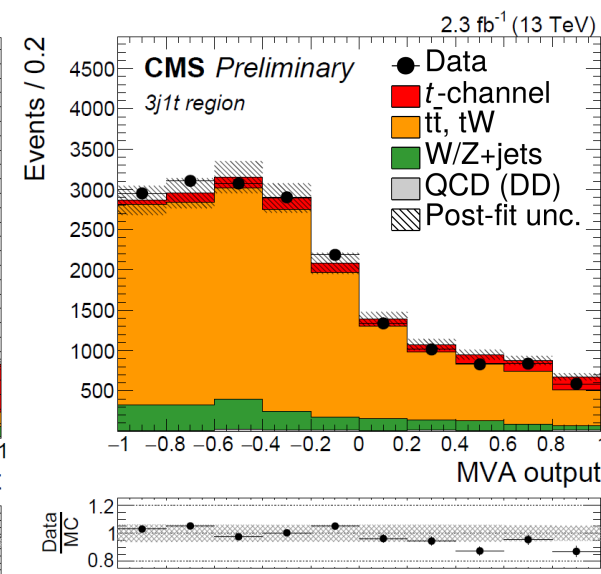
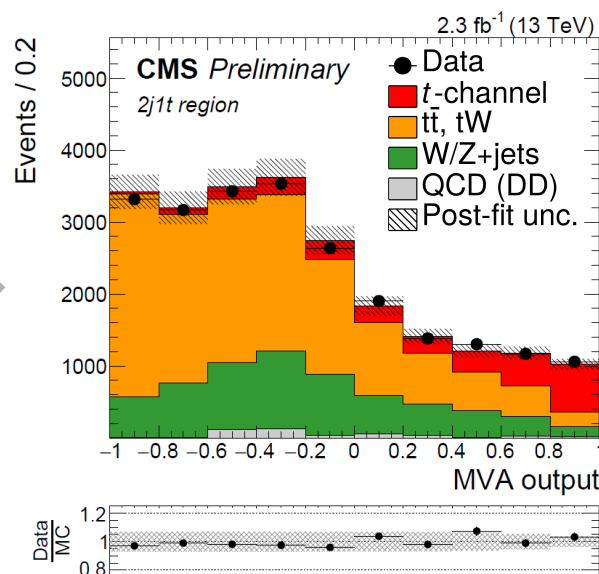


## ➤ analysis strategy

fit  $m_T(W) \rightarrow$  QCD yield



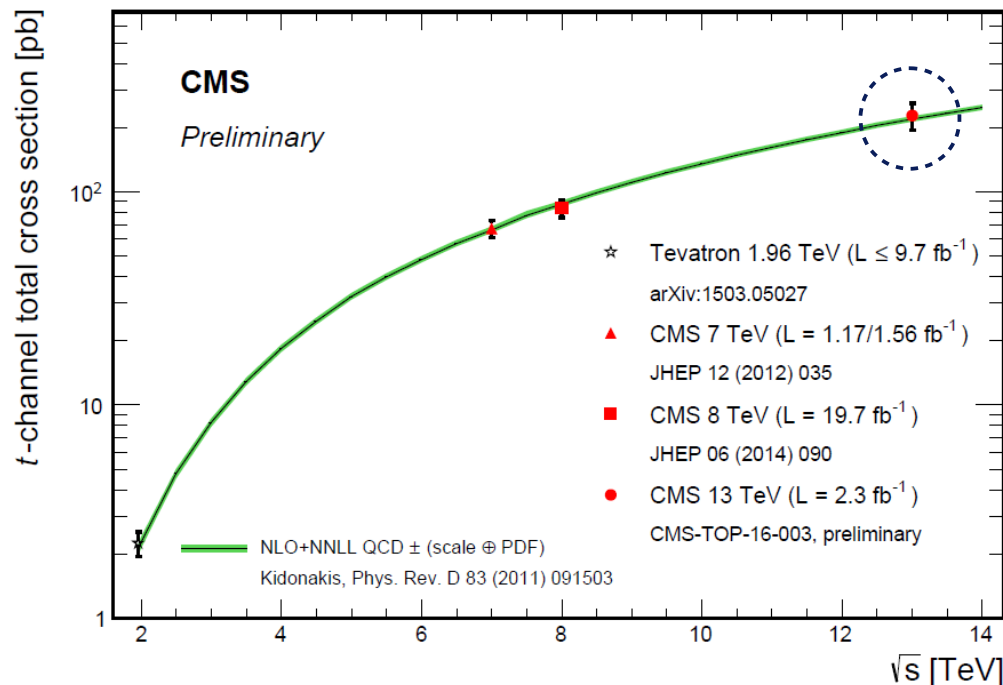
2<sup>nd</sup> fit using neural network discriminant  $\rightarrow$  signal yield





# t-channel cross section @ 13 TeV

- experimental uncertainties constrained in-situ (small compared to theo. unc.)
- largest single uncertainty: signal modeling (aMC@NLO ↔ Powheg)

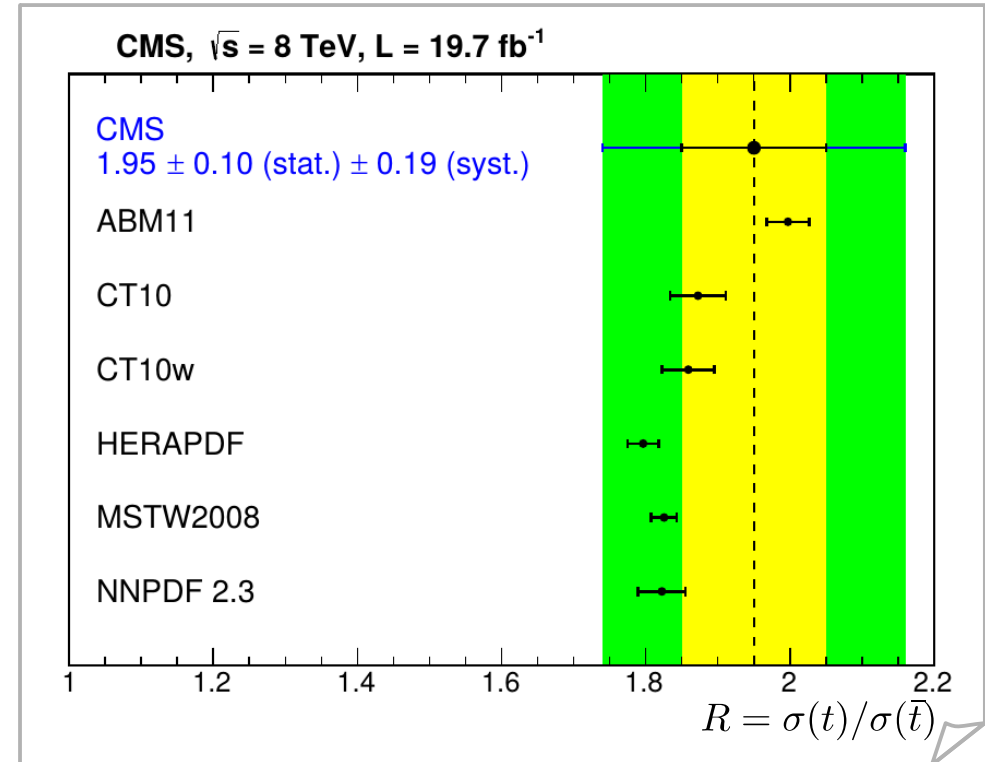
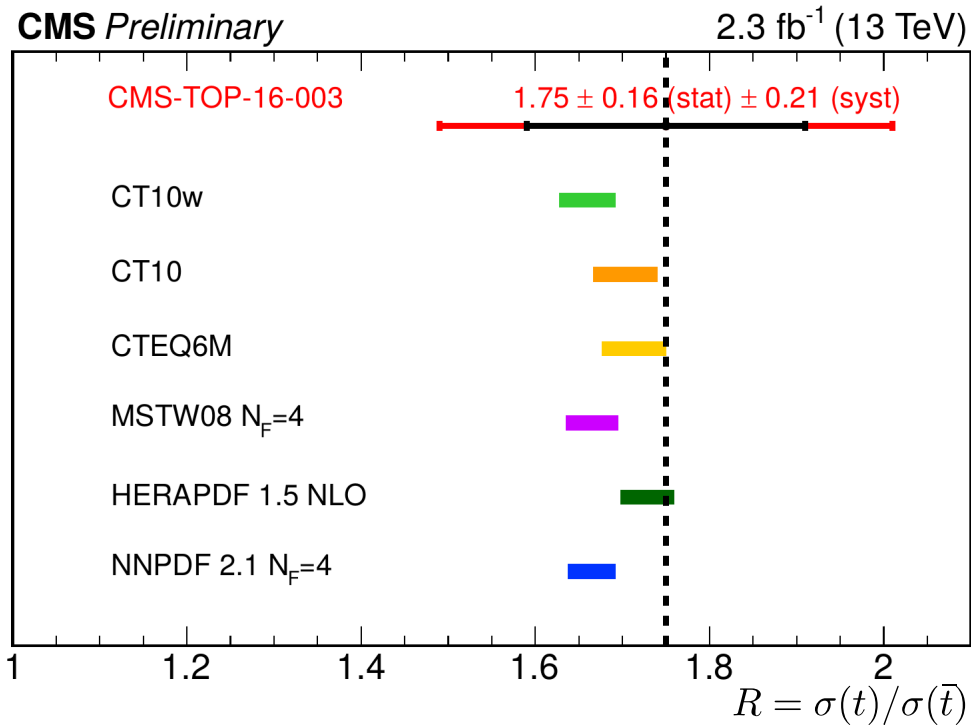


$$\begin{aligned}
 \sigma(t + \bar{t}) &= 228 \pm 4\% \text{ (stat.)} \pm 6\% \text{ (exp.)} \pm 12\% \text{ (theo.)} \pm 3\% \text{ (lumi.) pb} \\
 &= 228 \pm 15\% \text{ pb} \left[ \sigma^{\text{SM}} = 217_{-8}^{+9} \text{ pb} \right]
 \end{aligned}$$

- CKM element  $V_{tb}$  assuming  $|V_{tb}| \gg |V_{td}|, |V_{ts}|$   
 $|f_{LV} V_{tb}| = 1.02 \pm 0.07 \text{ (exp.)} \pm 0.02 \text{ (theo.)}$

# Cross section ratio

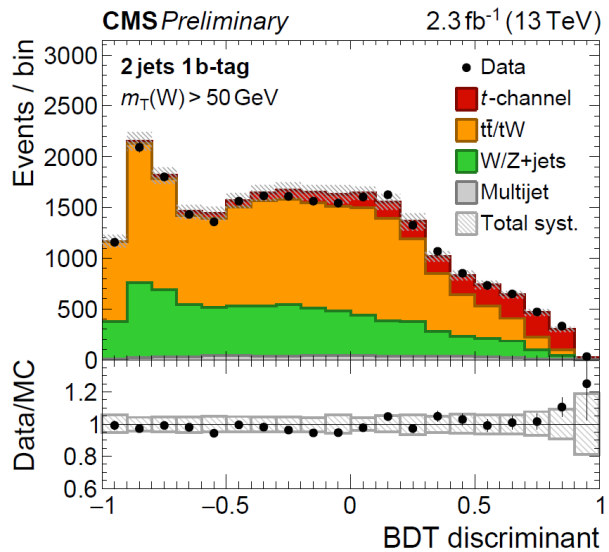
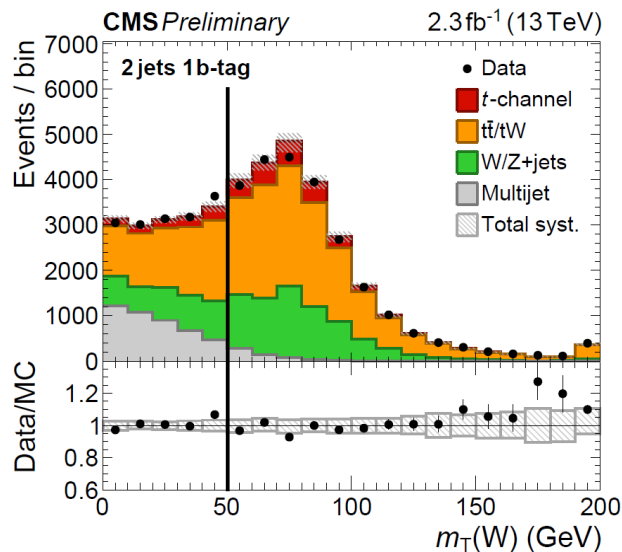
- strategy: perform separate fits to discriminant for  $\mu^+/\mu^-$  event  
→ ratio sensitive to PDF sets



- such measurements might provide input to PDF fits in the future

# t-channel differential @ 13 TeV

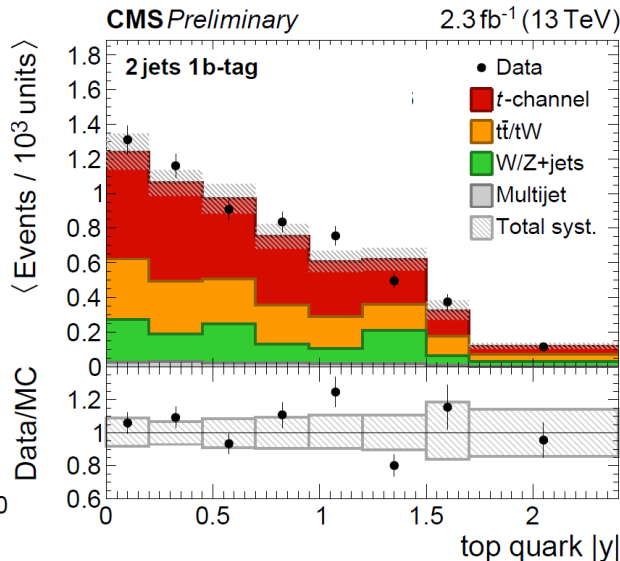
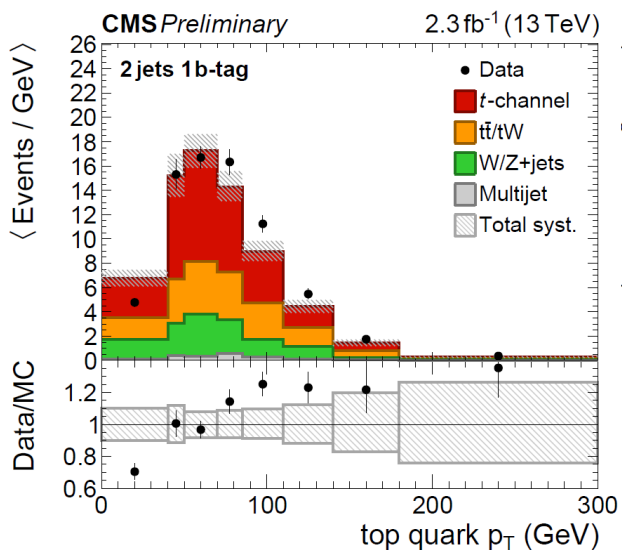
- estimate signal yield in bins of top quark  $p_T$  & rapidity  $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$
- perform multiple fits to  $m_T(W)$  & Boosted Decision Tree discriminant



– extended likelihood

- use antiisolated  $\mu$  data to model QCD shape
- fit shape of  $m_T(W)$  for events  $m_T(W) < 50$  GeV
- otherwise BDT discriminant

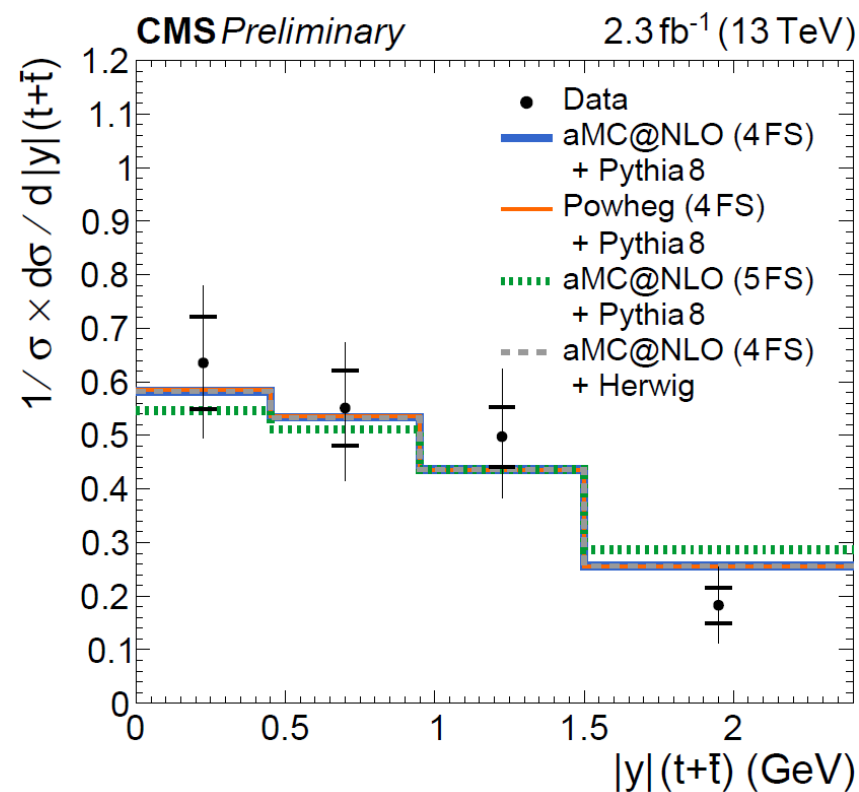
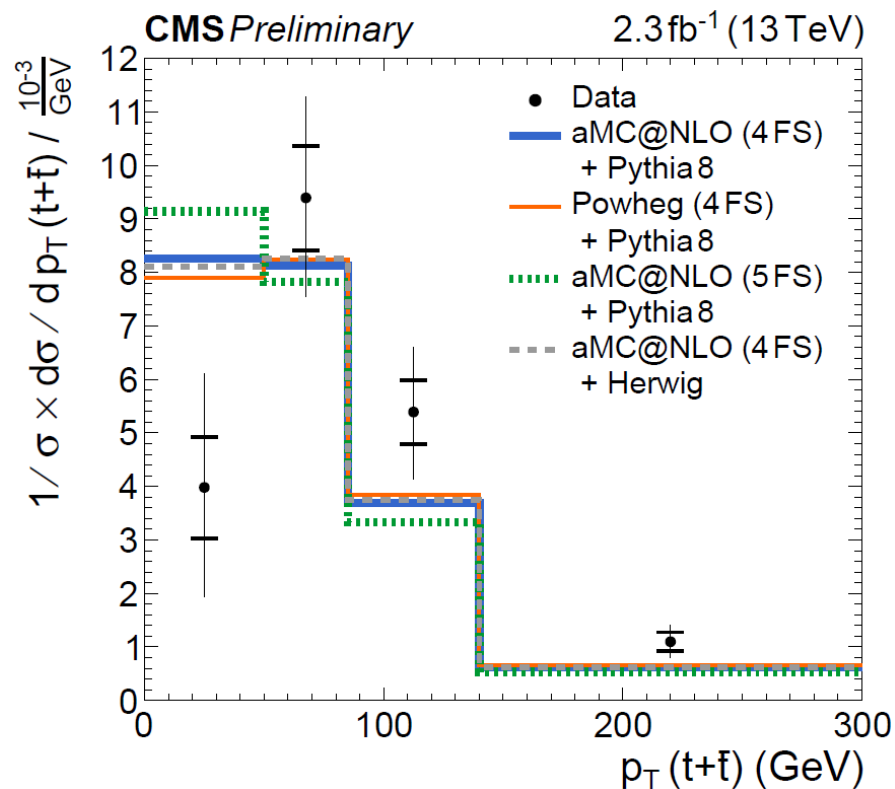
– modeling in signal-enhanced region ( $m_T(W) > 50$  GeV & BDT > 0.6)



– data display slightly harder  $p_T$  spectrum than simulation

# t-channel differential: Result

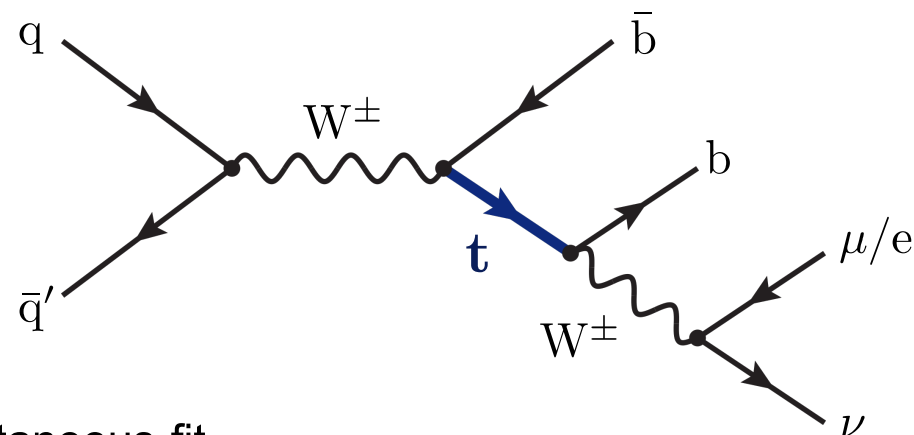
- use ML fit results to unfold to parton level



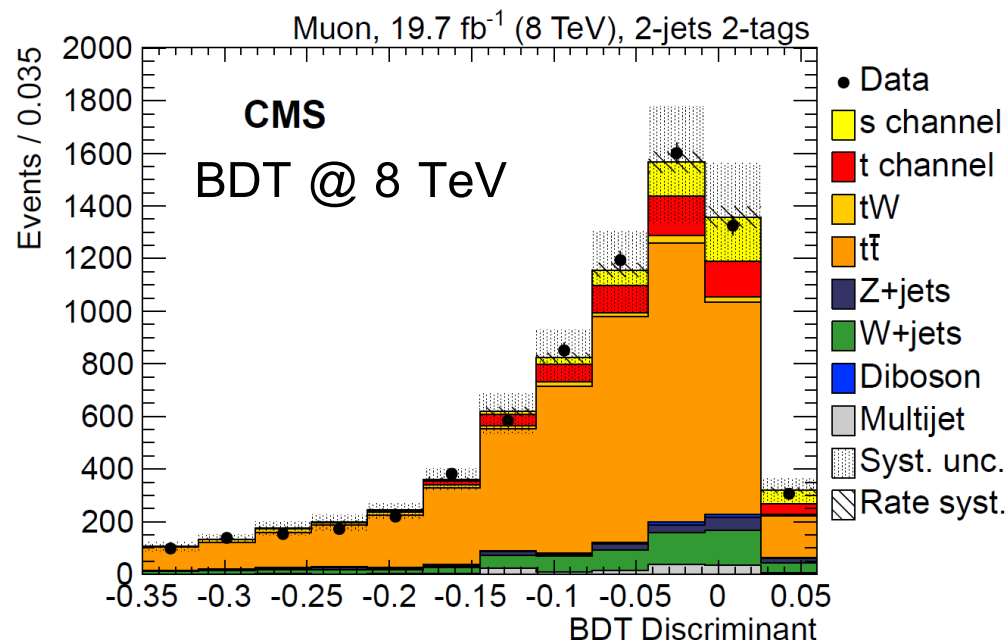
- data described by theoretical predictions within the relatively large uncertainties
- large rel. uncertainty in first  $p_T$  bin due to low acceptance & high sensitivity to systematic uncertainties

# s-channel @ 7,8 TeV

- signal region
  - 2 jets (both b-tagged), 1 isolated  $\mu/e$ ,  $\cancel{E}_T$
- analysis strategy
  - BDTs trained to separated signal from overwhelming  $t\bar{t}$  & W+jets
  - data-driven estimation of QCD
  - cross section estimated by performing simultaneous fit to BDT distribution in signal & control regions (2j1t, 3j2t)
  - syst. uncertainties externalized (largest: jet energy calibration, b-tagging, Q scale)



## ➤ result:



## significance per energy

7 TeV: observed  $0.9\sigma$  (expected  $0.5\sigma$ )

8 TeV: observed  $2.3\sigma$  (expected  $0.8\sigma$ )

## combined signal strength

$$\frac{\sigma_{\text{meas.}}}{\sigma_{\text{theo.}}} \equiv \beta_{\text{signal}} = 2.0 \pm 0.9$$

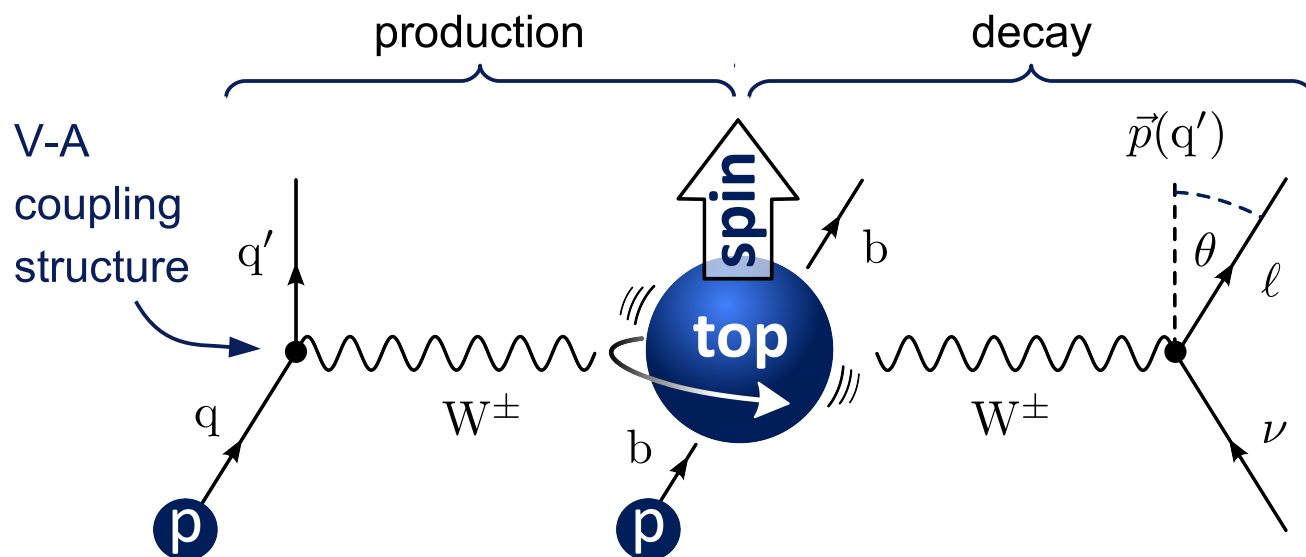
⇒ observed  $2.5\sigma$  (expected  $1.1\sigma$ )

# Single top: couplings

# Single top polarization @ 8 TeV

→ JHEP 04 (2016) 073

- SM: top quarks are produced polarized in t-channel along light jet ( $q'$ )



- define polarization angle in top quark rest frame

$$\cos \theta^* \propto \vec{p}_{q'}^{(top)} \cdot \vec{p}_\ell^{(top)}$$

- measure ...

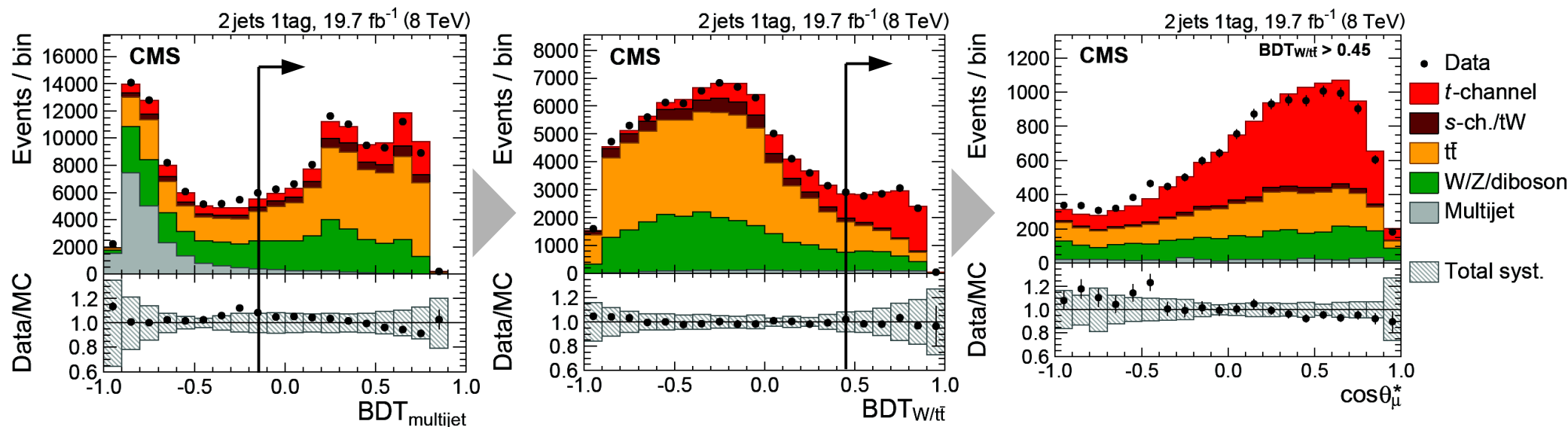
- differential cross section

$$1/\sigma \cdot d\sigma/d\cos\theta^*$$

- asymmetry

$$A = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \frac{1}{2} \alpha_\ell \cdot P_{top}$$

- strategy: select data in signal-enhanced phase space → unfolding

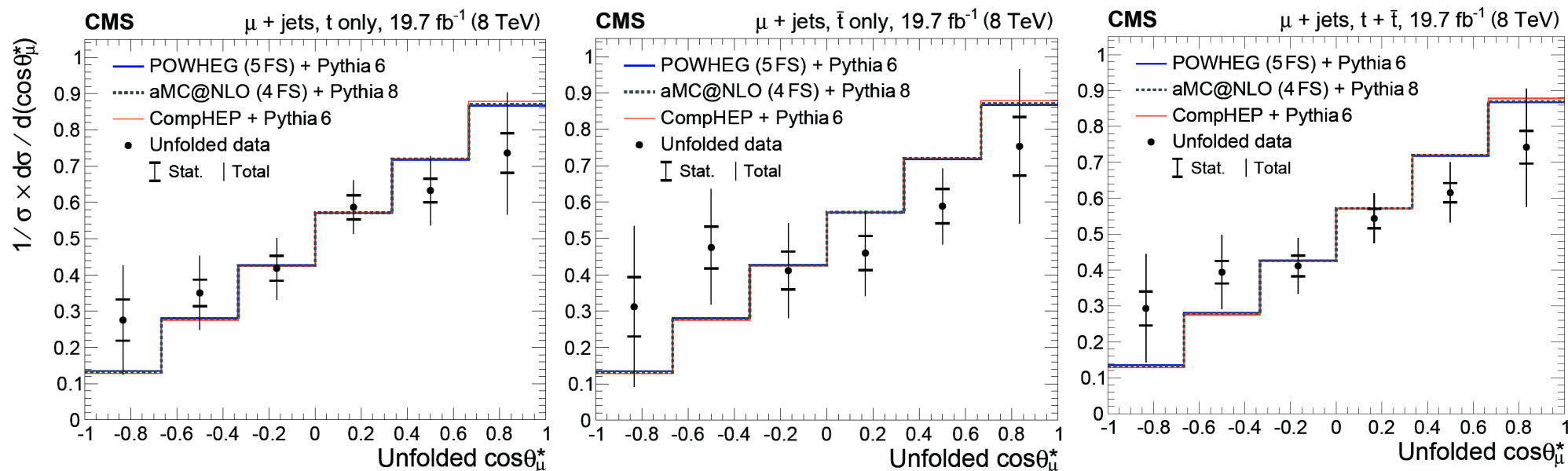




# Single top polarization: Result

→ JHEP 04 (2016) 073

## ➤ differential cross section



## ➤ asymmetry

– using linear fit

$$A_\mu(t) = 0.29 \pm 0.03 (\text{stat}) \pm 0.10 (\text{syst}) = 0.29 \pm 0.11$$

$$A_\mu(\bar{t}) = 0.21 \pm 0.05 (\text{stat}) \pm 0.13 (\text{syst}) = 0.21 \pm 0.14$$

$$A_\mu(t + \bar{t}) = 0.26 \pm 0.03 (\text{stat}) \pm 0.10 (\text{syst}) = 0.26 \pm 0.11$$

$$\left[ A_\mu^{(\text{SM})} = 0.44 \right]$$

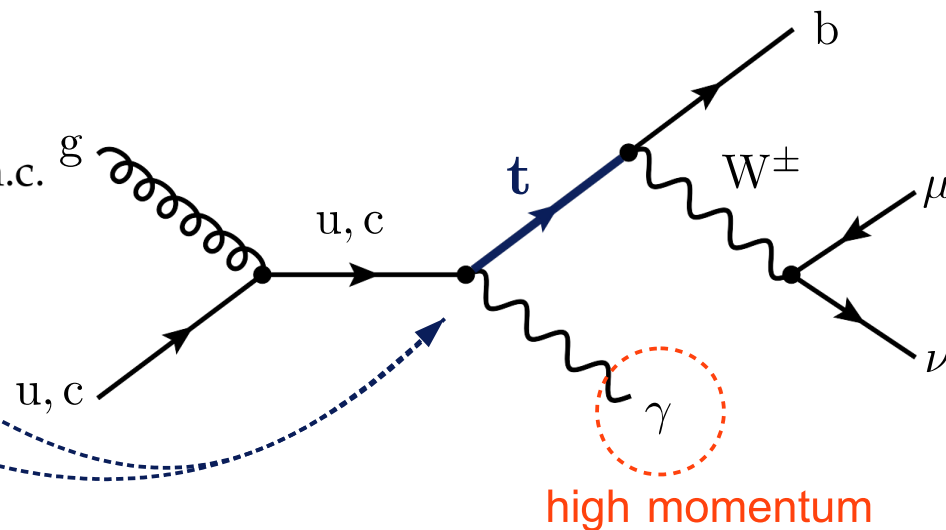
– largest syst. uncertainties:  $W + \text{jets}$  modeling,  $t\bar{t}$  modeling, jet energy/resolution calibration

➤ compatibility:  $p(\text{data}|\text{SM}) = 4.6\% \equiv 2.0\sigma$ ,  $p(\text{data}|A_\mu = 0) = 0.7\% \equiv 2.7\sigma$

## ➤ motivation

- highly suppressed in SM:  $\text{BR} \sim \mathcal{O}(10^{-14})$
- FCNC couplings from effective dim.-6 operators

$$\mathcal{L}_{\text{eff}} = -eQ_t \sum_{q=u,c} \bar{q} \frac{i\sigma^{\mu\nu} q_\nu}{\Lambda} (\kappa_{tq\gamma}^L P_L + \kappa_{tq\gamma}^R P_R) t A_\mu + \text{h.c.}$$

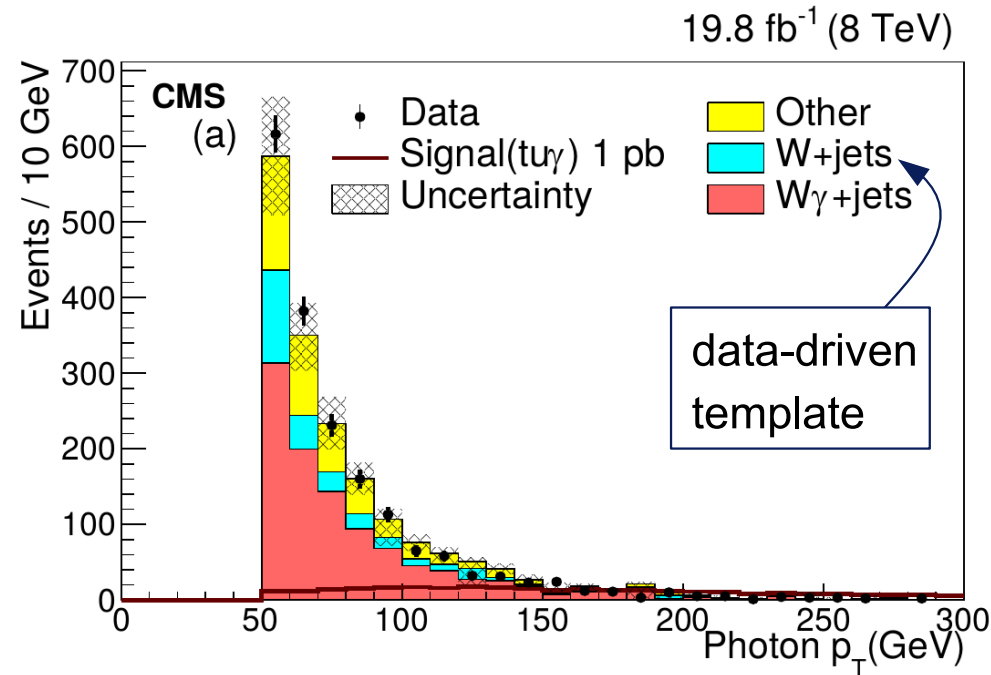


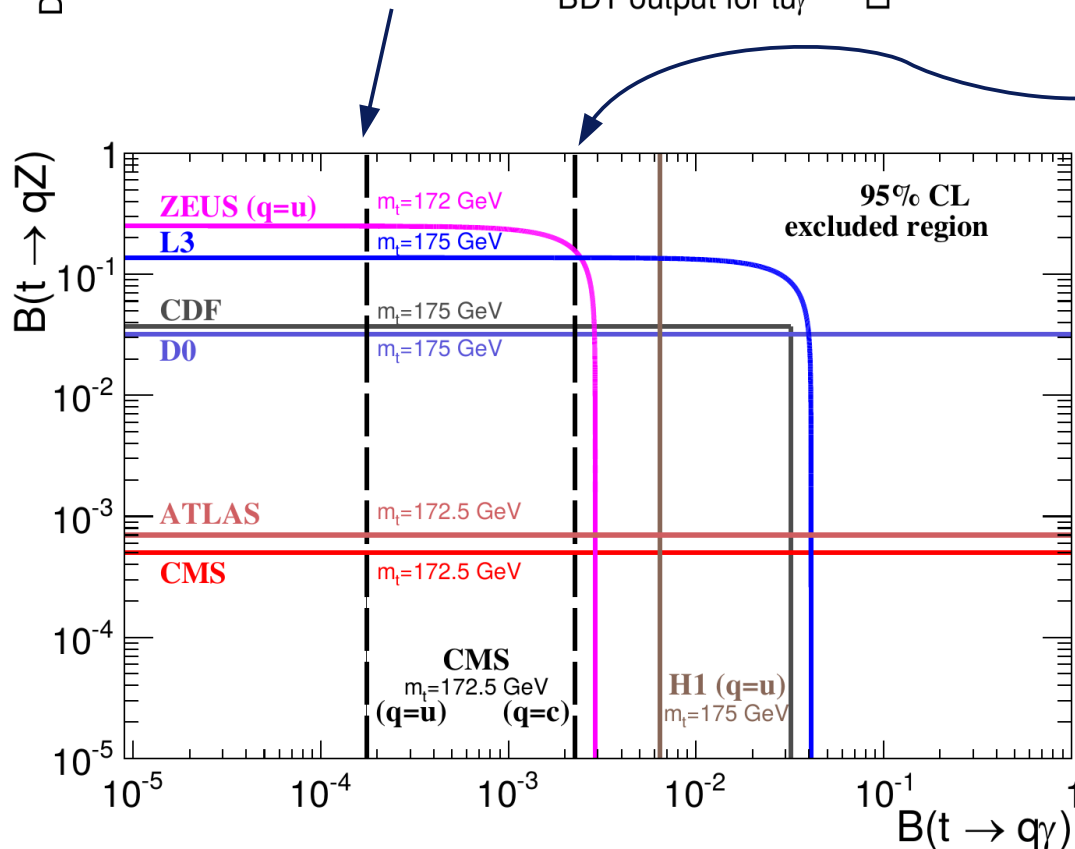
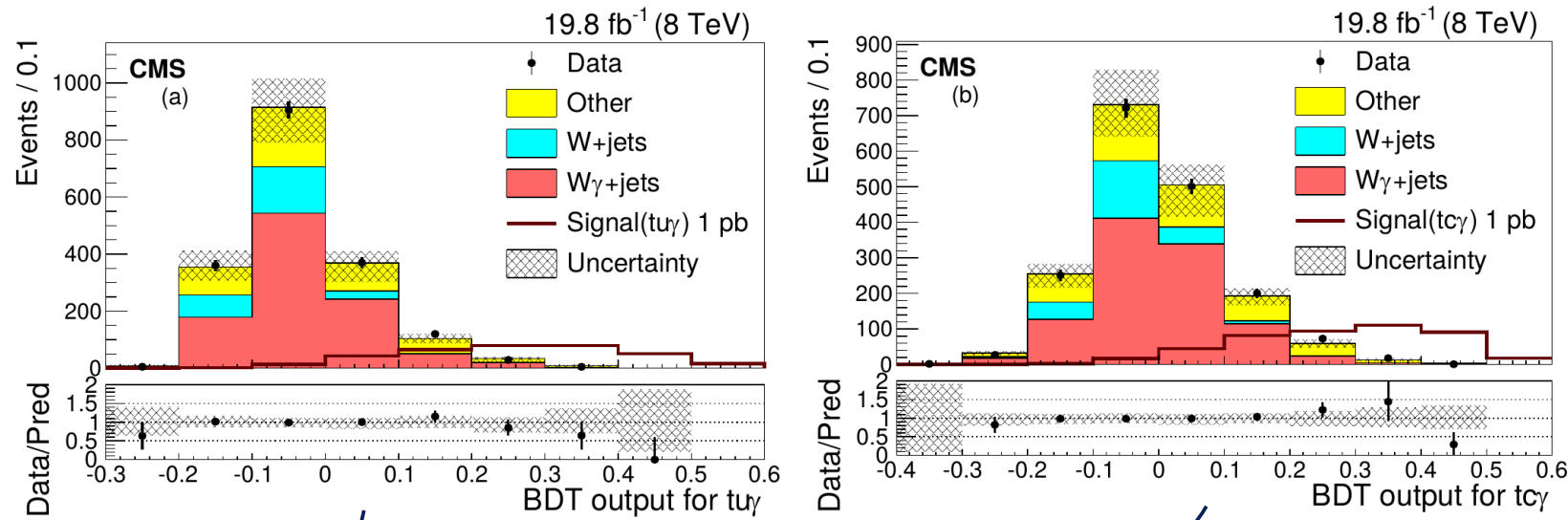
## ➤ signal signature:

- 1 b-tagged jet, 1 isolated  $\mu$ ,  $\cancel{E}_T$ , isolated  $\gamma$

## ➤ analysis strategy

- main backgrounds:  $W + \text{jets}$ ,  $W\gamma + \text{jets}$   
→ estimated from data using neural network
- signal extraction: BDTs for  $t \rightarrow \gamma u$ ,  $t \rightarrow \gamma c$
- input variables:  $p_T^\gamma$ ,  $p_T^\mu$ , b-tagging discriminant,  $p_T^b$ ,  $\cos \theta(t, \gamma)$ ,  $\Delta R(b, \gamma)$ ,  $\Delta R(\mu, \gamma)$ ,  $Q_\mu$ ,  $N(\text{extra jets})$

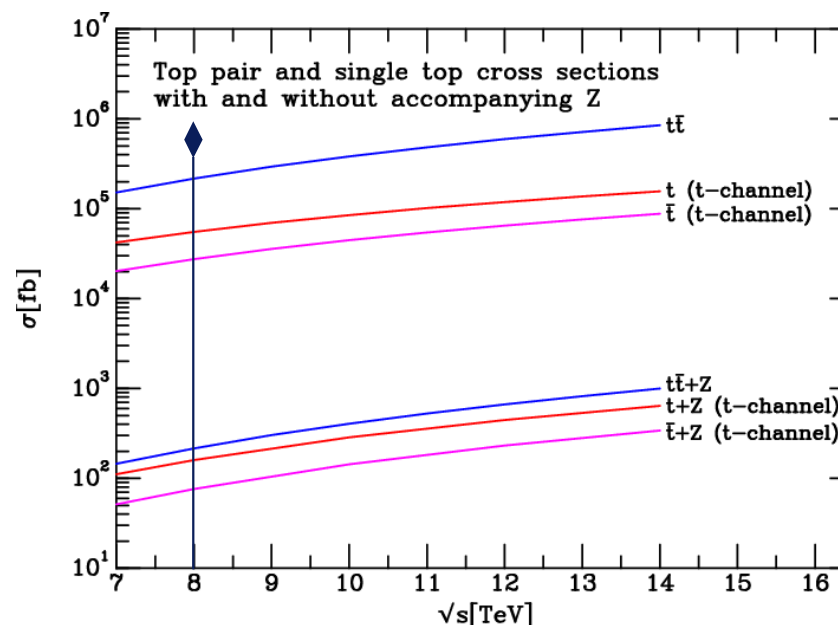
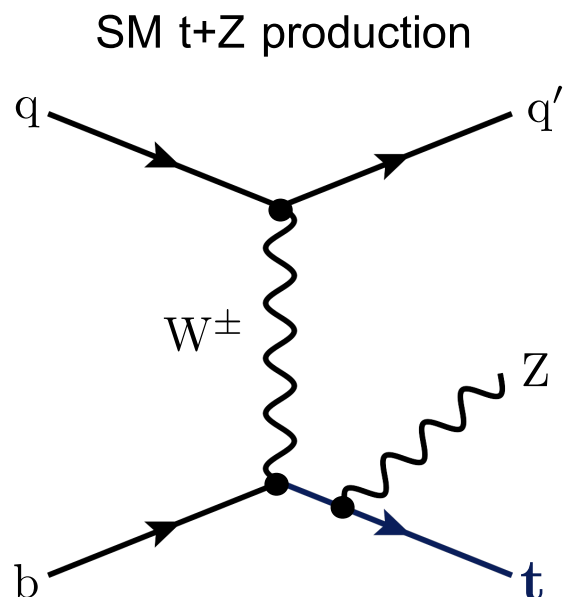




- largest uncertainties:  
W+jets background normalization,  
 $\mu/\gamma$  identification, jet calibration
- coupling limits converted to BRs
  - $\text{BR}(t \rightarrow u\gamma) < 1.3 \cdot 10^{-4}$
  - $\text{BR}(t \rightarrow c\gamma) < 1.7 \cdot 10^{-3}$
- results also interpreted as limits  
on cross section in fiducial region  
(→ backup)



# SM $t + Z$ @ 8 TeV

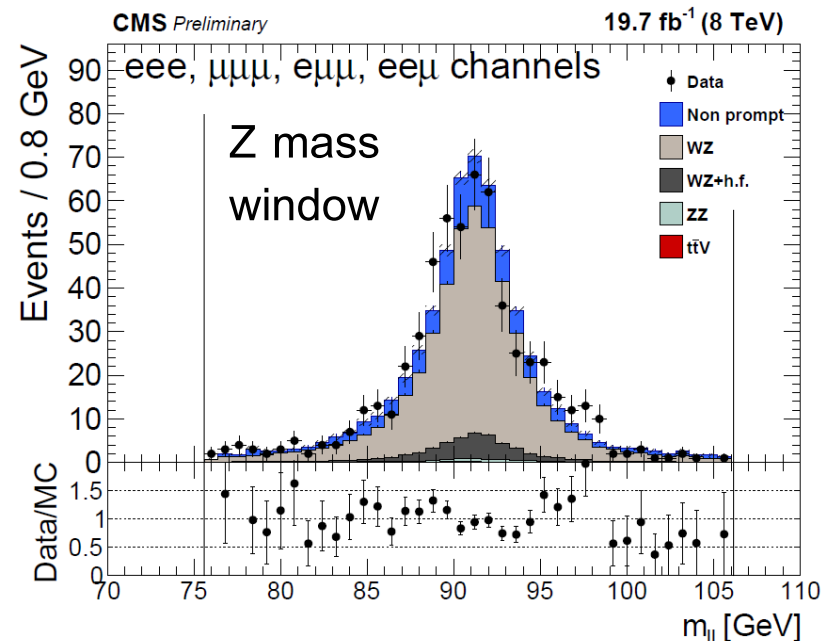


J. Campbell et. al.,  
Phys. Rev. D87 2013  
arXiv:1302.3856

→ can be enhanced  
through BSM FCNC  
 $t g q, t Z q$  couplings

## ➤ event selection

- 3 isolated leptons:  $eee, ee\mu, e\mu\mu, \mu\mu\mu$   
→ oppositely charged leptons in Z mass window
- SM  $tZq$ : >1 jets with at least 1 b-tag
- inverting b-tagging: Drell-Yan/WZ control region





# SM $t + Z$ results

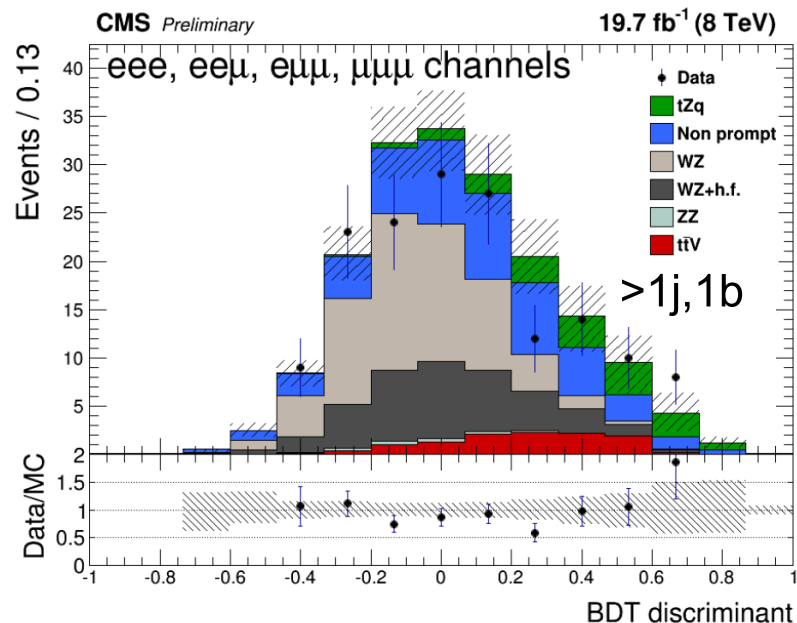
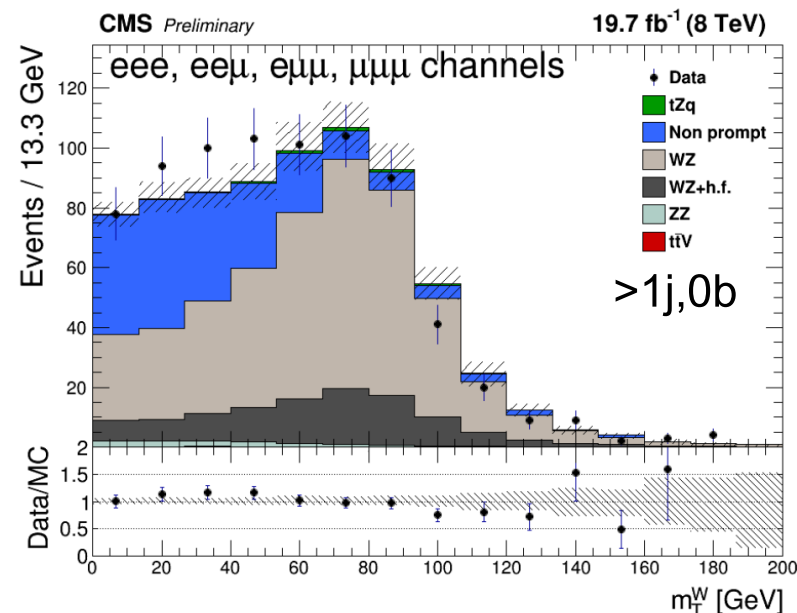
## ➤ analysis strategy

- shape of non prompt lepton events estimated by inverting lepton isolation
- BDT trained to separate SM  $tZq$  from  $WZ$  &  $ttZ$
- signal & background yields estimated by simultaneous fit to transverse  $W$  boson mass (CR) & BDT (SR)
- systematic uncertainties profiled

## ➤ result

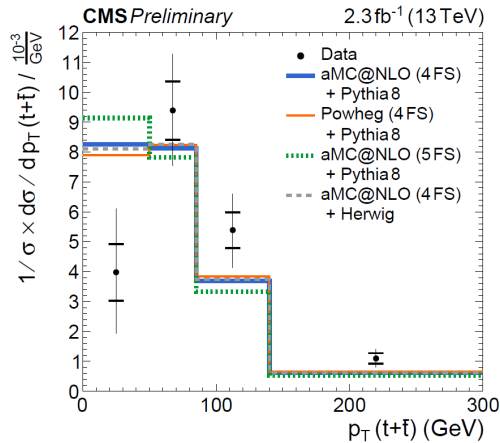
$$\sigma_{tZq}^{\text{meas.}} = 10^{+8}_{-7} \text{ fb} \quad \left[ \sigma_{tZq}^{\text{theo.}} = 8.2^{+0.59}_{-0.03} (\text{scale}) \text{ fb} \right]$$

observed:  $2.4\sigma$  (expected:  $1.8\sigma$ )



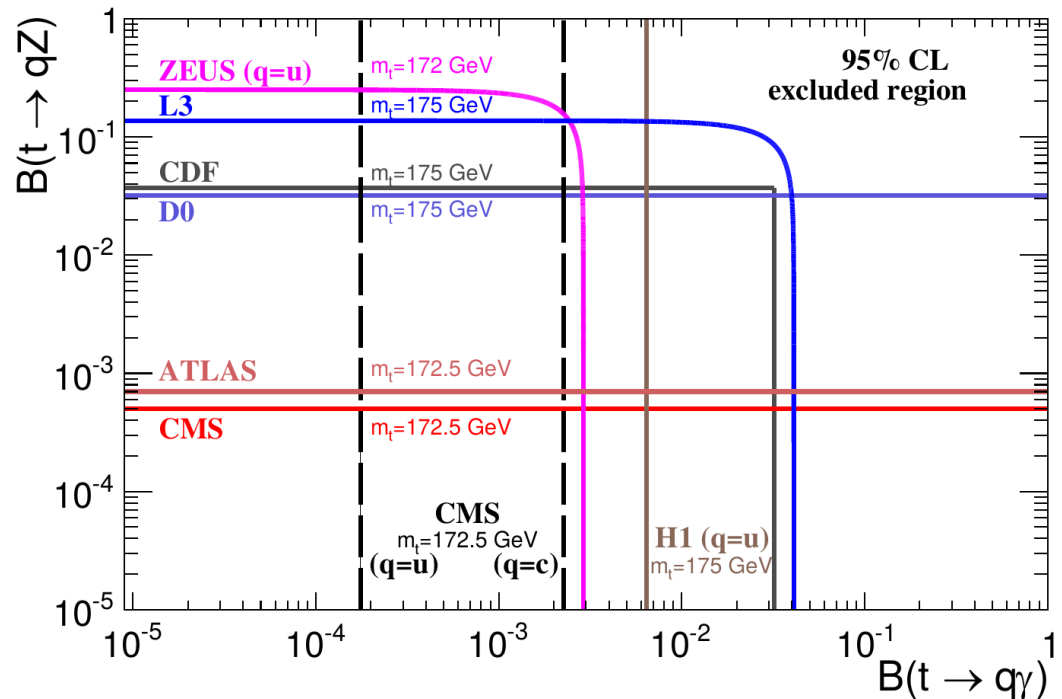
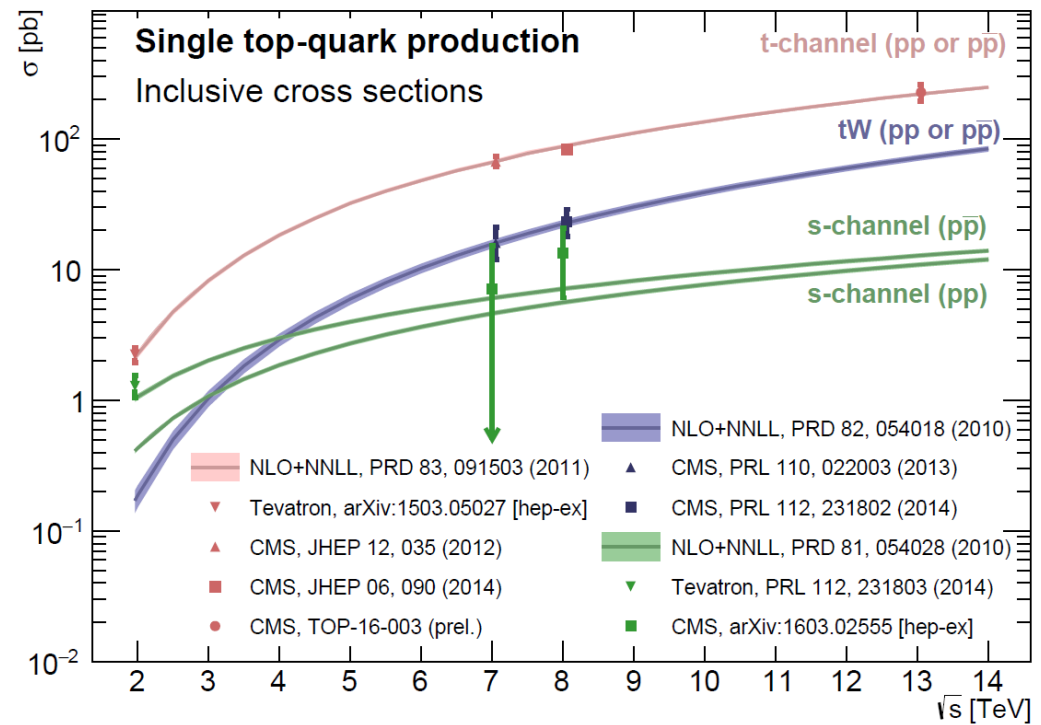
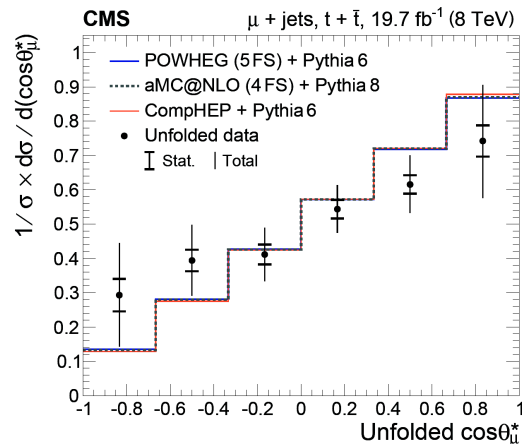
# Conclusion

- new cross section measurements
  - inclusive t-channel cross sections
  - differential t-channel cross section



- s-channel cross section

- new results on single top couplings
  - search for  $t + \gamma/Z$  production
  - single top polarization

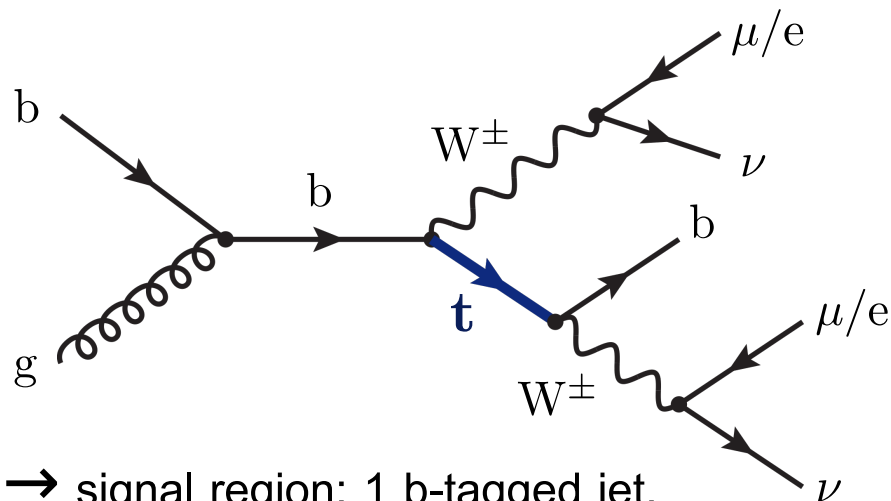


# Backup



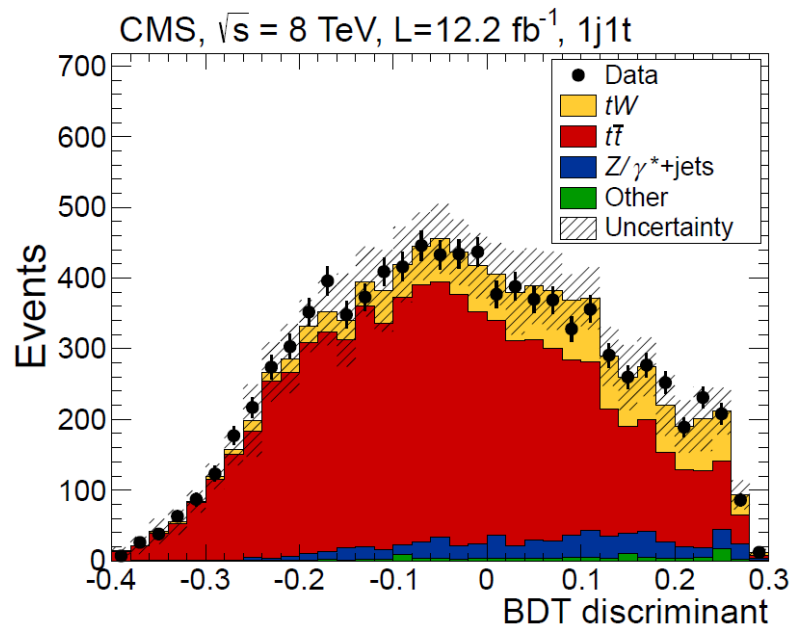
# Observation of $tW$ @ 8 TeV

→ PRL 112 (2014)  
→ CMS PAS TOP-15-019



→ signal region: 1 b-tagged jet,  
2 leptons,  $\cancel{E}_T$

– contamination from  $t\bar{t}$  still high after  
event selection → train Boosted Decision Tree

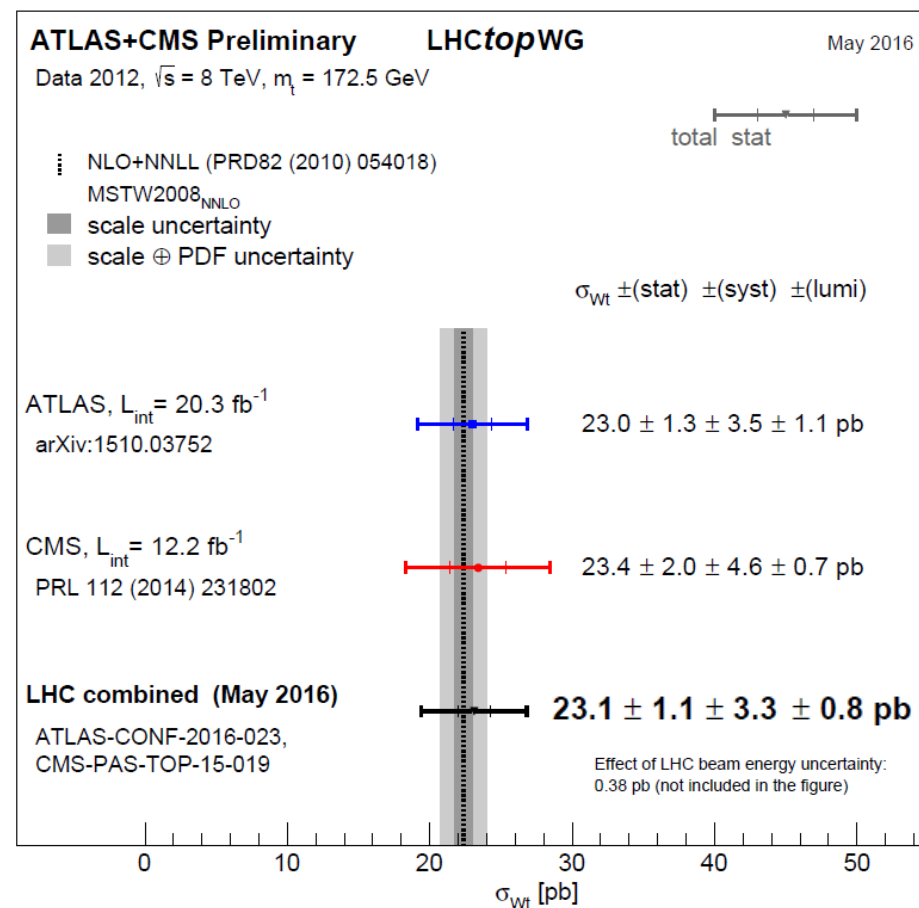


➤ result

$$\sigma_{tW} = 23.4 \pm 5.4 \text{ pb}$$

$$\left[ \sigma_{tW}^{(\text{NLO+NNL})} = 22.6 \pm 1.5 \text{ pb} \right]$$

➤ legacy 8 TeV combination with ATLAS



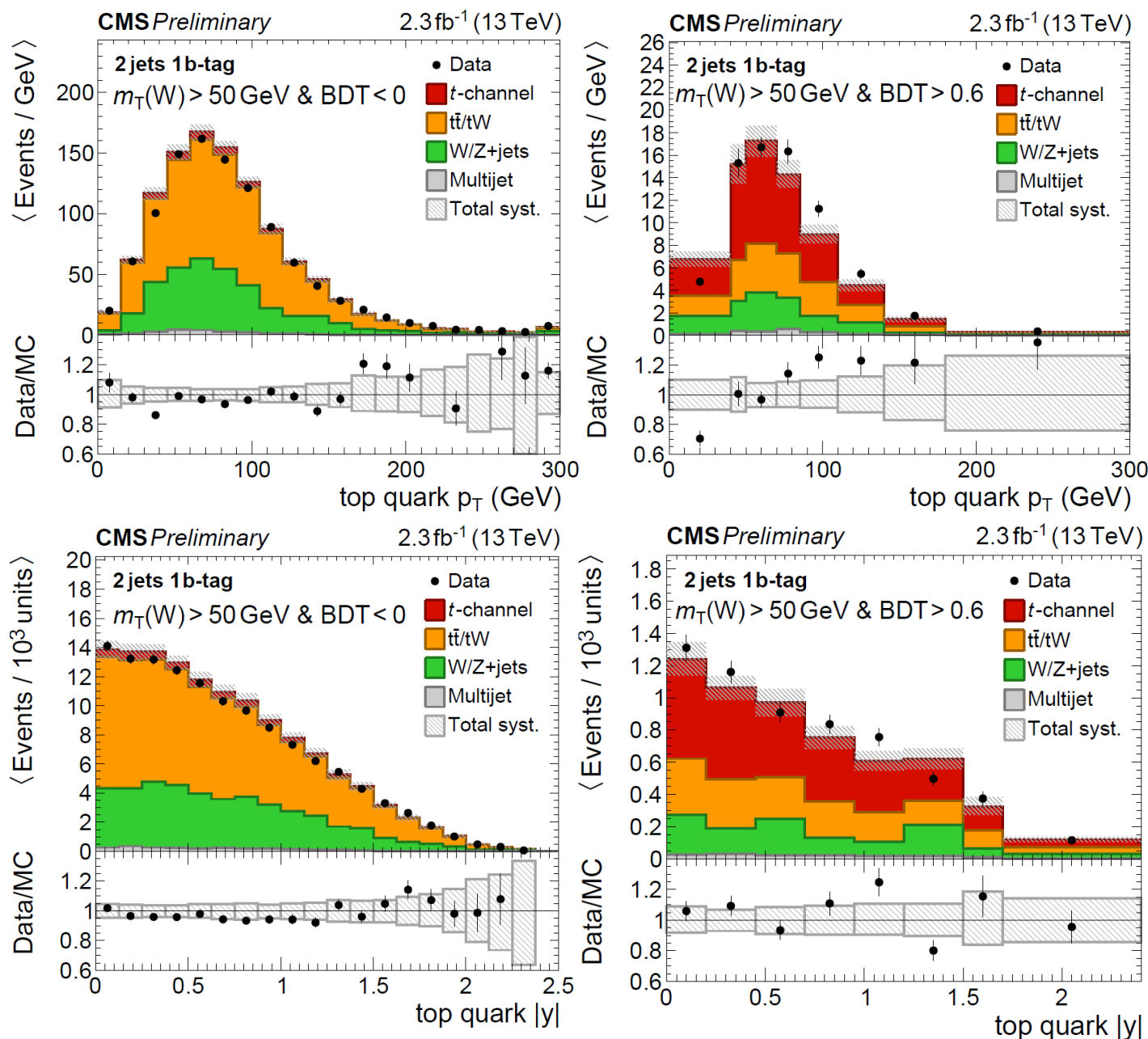
# t-channel @ 13 TeV: Uncertainty

uncertainty source	$\Delta\sigma_{t\text{-ch.},t+\bar{t}}/\sigma_{t\text{-ch.},t+\bar{t}}^{\text{obs}}$	$\Delta\sigma_{t\text{-ch.},t}/\sigma_{t\text{-ch.},t}^{\text{obs}}$	$\Delta\sigma_{t\text{-ch.},\bar{t}}/\sigma_{t\text{-ch.},\bar{t}}^{\text{obs}}$
JES	$\pm 4.9\%$	$\pm 5.6\%$	$\pm 3.7\%$
JER	$\pm 0.7\%$	$\pm 0.2\%$	$\pm 1.5\%$
b-tagging efficiency	$\pm 2.3\%$	$\pm 2.1\%$	$\pm 1.6\%$
mis-tagging efficiency	$\pm 0.8\%$	$\pm 1.2\%$	$\pm 0.4\%$
lepton reconstruction/trigger	$\pm 2.5\%$	$\pm 2.0\%$	$\pm 2.9\%$

uncertainty source	$\Delta\sigma_{t\text{-ch.},t+\bar{t}}/\sigma_{t\text{-ch.},t+\bar{t}}^{\text{obs}}$	$\Delta\sigma_{t\text{-ch.},t}/\sigma_{t\text{-ch.},t}^{\text{obs}}$	$\Delta\sigma_{t\text{-ch.},\bar{t}}/\sigma_{t\text{-ch.},\bar{t}}^{\text{obs}}$
uncertainty of the fit (stat. + prof. unc.)	$\pm 6.8\%$	$\pm 7.4\%$	$\pm 11.9\%$
statistical uncertainty	$\pm 4.0\%$	$\pm 4.7\%$	$\pm 7.6\%$
profiled uncertainties	$\pm 5.5\%$	$\pm 5.7\%$	$\pm 9.2\%$
MC statistics	$\pm 2.8\%$	$\pm 3.4\%$	$\pm 4.0\%$
pileup	$-0.2/+0.1\%$	$-0.5/+0.4\%$	$-0.1/+0.7\%$
experimental uncertainty	$-6.2/+6.2\%$	$-6.7/+6.7\%$	$-10.0/+10.0\%$
Signal modeling	$\pm 7.9\%$	$\pm 10.1\%$	$\pm 8.2\%$
$t\bar{t}$ modeling	$\pm 4.3\%$	$\pm 3.9\%$	$\pm 4.6\%$
W+jets modeling	$-2.1/+1.7\%$	$-1.6/+1.1\%$	$-2.8/+2.3\%$
$Q^2$ scale $t$ -channel	$-5.7/+7.0\%$	$-7.1/+5.1\%$	$-6.1/+6.9\%$
$Q^2$ scale $t\bar{t}$	$-2.7/+4.1\%$	$-2.5/+4.0\%$	$-3.9/+3.4\%$
$Q^2$ scale $tW$	$-0.3/+0.5\%$	$-0.4/+0.3\%$	$-1.1/+0.4\%$
$Q^2$ scale W+jets	$-2.7/+3.0\%$	$-2.5/+4.2\%$	$-5/+2.4\%$
PDF uncertainty	$-3.0/+2.6\%$	$-3.1/+3.2\%$	$-3.7/+4.2\%$
top $p_T$ modeling	$\pm 0.1\%$	$\pm 0.1\%$	$\pm 0.2\%$
total theory uncertainties	$-12.1/+12.6$	$-13.8/+13.6$	$-13.5/+13.4\%$
luminosity	$\pm 2.7\%$	$\pm 2.7\%$	$\pm 2.7\%$
total uncertainty	$-14.5/+14.8\%$	$-16.3/+16.1\%$	$-18.6/+18.6\%$

# Differential t-channel @ 13 TeV

- modeling in signal-depleted & signal-enhanced regions using additional BDT selection



- signal-depleted region well modeled by simulation
- data display slightly harder  $p_T$  spectrum than simulation for signal
- rapidity well described in both regions

# Top polarization uncertainties

	$\delta A_\mu(t)/10^{-2}$	$\delta A_\mu(\bar{t})/10^{-2}$	$\delta A_\mu(t + \bar{t})/10^{-2}$
Statistical	3.2	4.6	2.6
ML fit uncertainty	0.7	1.2	0.6
Diboson bkg. fraction	<0.1	<0.1	<0.1
Z/ $\gamma^*$ +jets bkg. fraction	<0.1	<0.1	<0.1
s-channel bkg. fraction	0.3	0.2	0.2
tW bkg. fraction	0.1	0.7	0.2
Multijet events shape	0.5	0.7	0.5
Multijet events yield	1.9	1.2	1.7
b tagging	0.7	1.2	0.9
Mistagging	<0.1	0.1	<0.1
Jet energy resolution	2.7	1.8	2.0
Jet energy scale	1.3	2.6	1.1
Unclustered $\cancel{E}_T$	1.1	3.3	1.3
Pileup	0.3	0.2	0.2
Lepton identification	<0.1	<0.1	<0.1
Lepton isolation	<0.1	<0.1	<0.1
Muon trigger efficiency	<0.1	<0.1	<0.1
Top quark $p_T$ reweighting	0.3	0.3	0.3
W+jets W boson $p_T$ reweighting	0.1	0.1	0.1
W+jets heavy-flavour fraction	4.7	6.2	5.3
W+jets light-flavour fraction	<0.1	<0.1	0.1
W+jets $\cos\theta_\mu^*$ reweighting	2.9	3.4	3.1
Unfolding bias	2.5	4.2	3.1
Generator model	1.6	3.5	0.3
Top quark mass	1.9	2.9	1.8
PDF	0.9	1.6	1.2
t-channel renorm./fact. scales	0.2	0.2	0.2
t $\bar{t}$ renorm./fact. scales	2.2	3.4	2.7
t $\bar{t}$ ME/PS matching	2.2	0.5	1.6
W+jets renorm./fact. scales	3.7	4.6	4.0
W+jets ME/PS matching	3.8	3.0	3.4
Limited MC events	2.1	3.2	1.8
Total uncertainty	10.5	13.8	10.5

# s-channel systematics

Source	Uncertainty (%)				
	$\mu, 7 \text{ TeV}$	$\mu, 8 \text{ TeV}$	e, 8 TeV	$\mu + e, 8 \text{ TeV}$	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 $\cancel{E}_T$	5	8	2	6	5
$\mu_R, \mu_F$ 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

$\sigma_s = 7.1 \pm 8.1$  (stat + syst) pb, muon channel, 7 TeV;

$\sigma_s = 11.7 \pm 7.5$  (stat + syst) pb, muon channel, 8 TeV;

$\sigma_s = 16.8 \pm 9.1$  (stat + syst) pb, electron channel, 8 TeV;

$\sigma_s = 13.4 \pm 7.3$  (stat + syst) pb, combined, 8 TeV.

$$\left[ \sigma_{s\text{-ch.}}^{\text{SM}, 7 \text{ TeV}} = 4.6 \pm 0.2 \text{ pb} \right]$$

$$\left[ \sigma_{s\text{-ch.}}^{\text{SM}, 8 \text{ TeV}} = 5.6 \pm 0.2 \text{ pb} \right]$$

# FCNC $t\gamma q$

## ➤ fiducial selection

Object	Requirement
Single muon	$p_T > 26 \text{ GeV},  \eta  < 2.1$
Veto for additional muons	$p_T > 10 \text{ GeV},  \eta  < 2.5$
Electron veto	$p_T > 20 \text{ GeV},  \eta  < 2.5$
Single photon	$p_T > 50 \text{ GeV},  \eta  < 2.5$ ( $1.44 <  \eta  < 1.56$ excluded)
At least one jet ( $N_{\text{b jet}} < 2$ )	$p_T > 30 \text{ GeV},  \eta  < 2.5$
Missing $p_T$	$p_T^{\text{miss}} > 30 \text{ GeV}$
Muon, jets, and photons	$\Delta R(\mu, \gamma) \text{ and } \Delta R(\text{jet}, \gamma) > 0.7$
Reconstructed top quark mass	$130 < m_{\mu\nu b} < 220 \text{ GeV}$

## ➤ limits

Fiducial region	Channel	$N_{\text{obs}}$	$N_{\text{SM}}$	$\epsilon$	$\sigma_{\text{fid}}^{95\%} \text{ (fb)}$
Basic selection	$\text{tu}\gamma$	1794	$1805 \pm 215$	0.16	122
	$\text{tc}\gamma$			0.19	103
Basic selection and $N_{\text{b jet}} = 1$	$\text{tu}\gamma$	275	$258 \pm 49$	0.11	47
	$\text{tc}\gamma$			0.14	39



# FCNC $t\gamma q$ uncertainties

Type	Source	$t\bar{u}\gamma$ (%)	$t\bar{c}\gamma$ (%)
Rate	Integrated luminosity	1.8	4
	Background normalization (W + jets)	5.6	3
	Background normalization (W $\gamma$ + jets)	2.5	1.1
	Other background normalizations	<1	1
Rate+Shape	Trigger efficiency	2.2	0.4
	Pileup effects	7	2.3
	Lepton identification and isolation	<1	4.4
	Photon identification and isolation	1.9	4.5
	Photon energy scale	<1	3.1
	b tagging and mistag efficiency	1.1	4
	Jet energy scale	2.9	2.2
	Jet energy resolution	2.1	3.4
	PDF	3.1	<1
	Scale	1	2.4
	Top quark mass	2.5	1



# $t+Z$ FCNC diagrams

