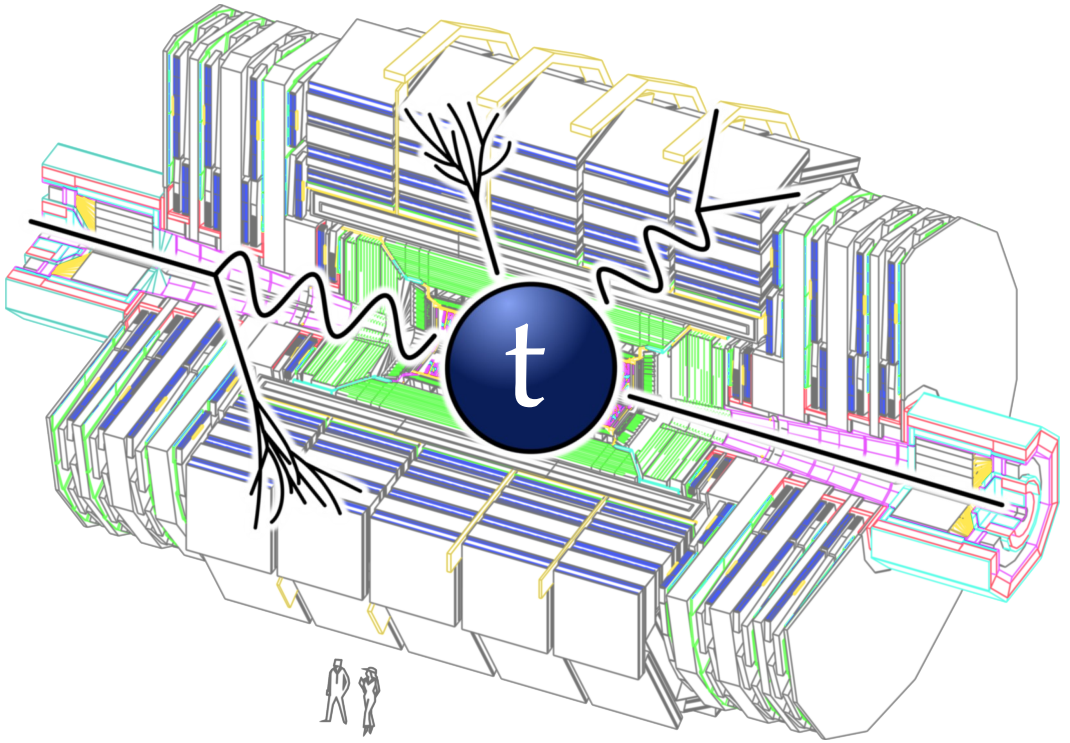


Single Tops @ CMS

3rd Single Top Workshop

Matthias Komm

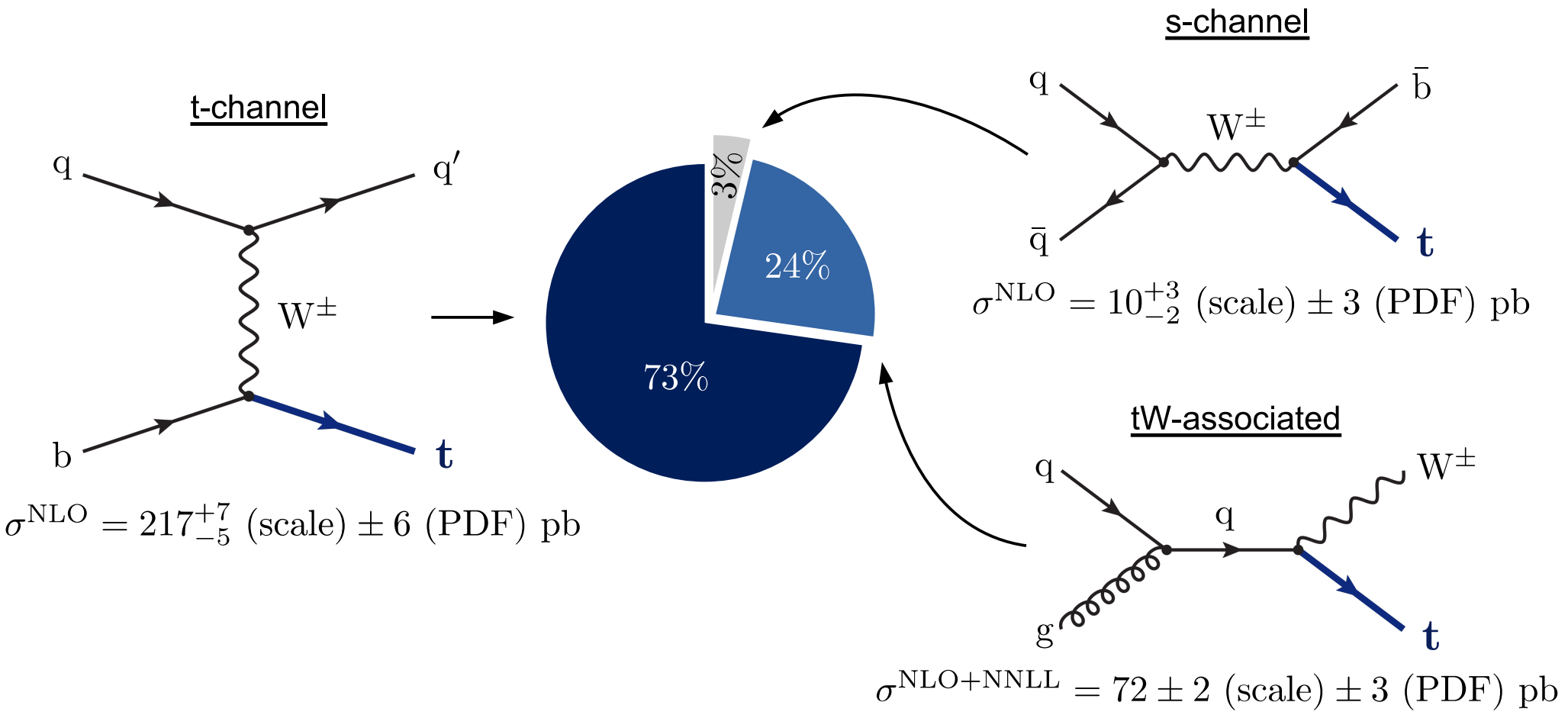
UCL Université catholique de Louvain

fnrs LA LIBERTÉ DE CHERCHER

Introduction

→ HATHORv2.1, arXiv:1007.1327 & arXiv:1406.4403
→ N. Kidonakis, arXiv:1005.4451 & arXiv:1311.0283

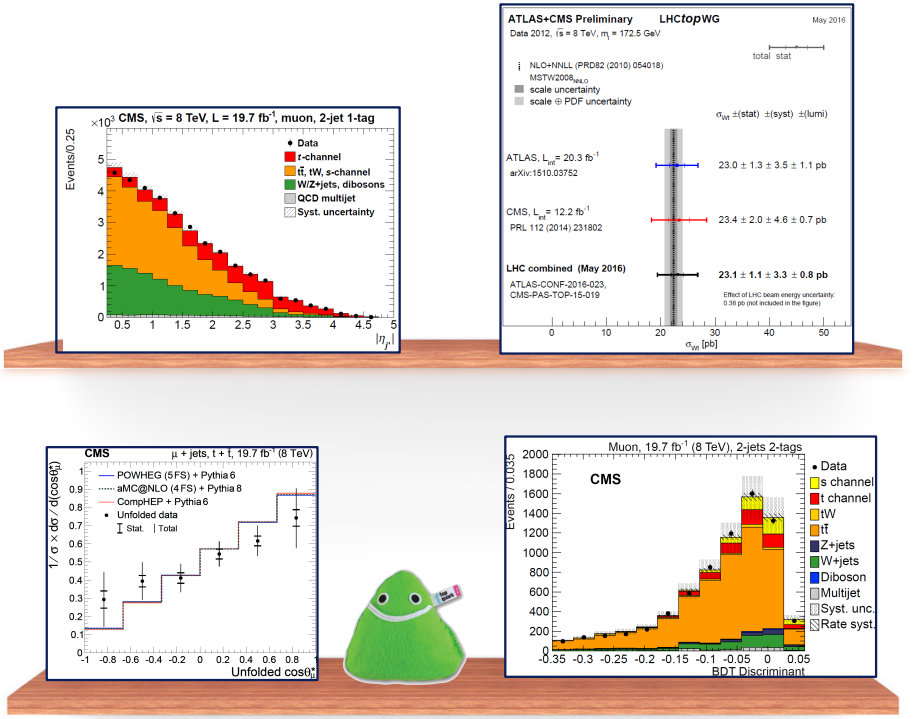
- production of single top quarks at **13 TeV** (PDF4LHC, $m_t = 172.5$)



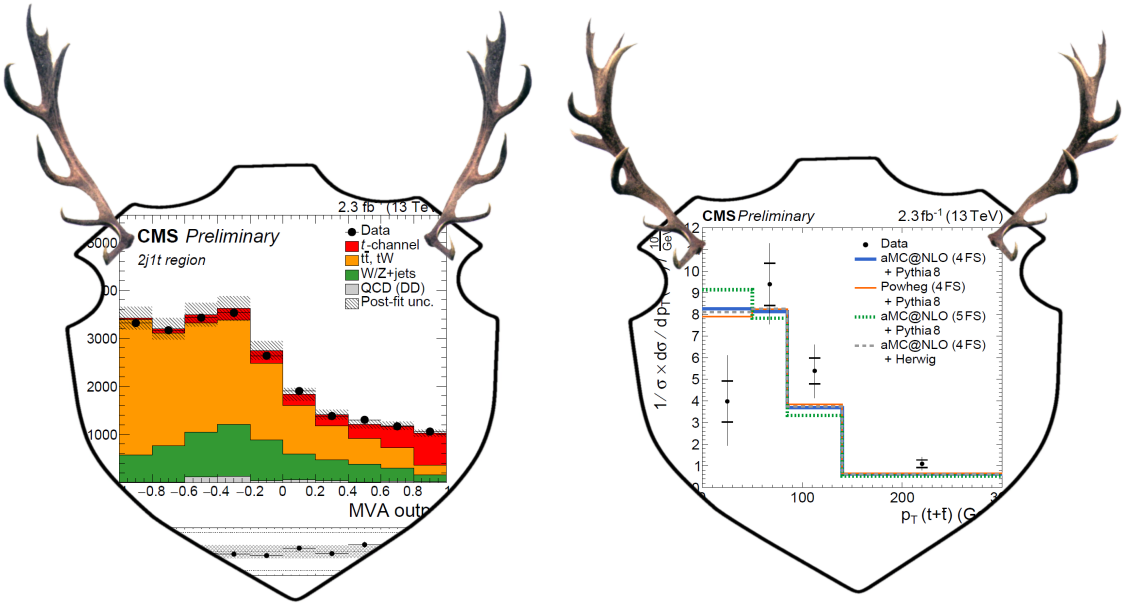
- why is it interesting?
  - probe CKM matrix element V_{tb}
  - probe alternative production mechanism (e.g. heavy bosons, FCNC)
  - probe electroweak coupling structure (e.g. anomalous couplings, polarization)
  - probe PDFs (e.g. charge ratio)

Outline

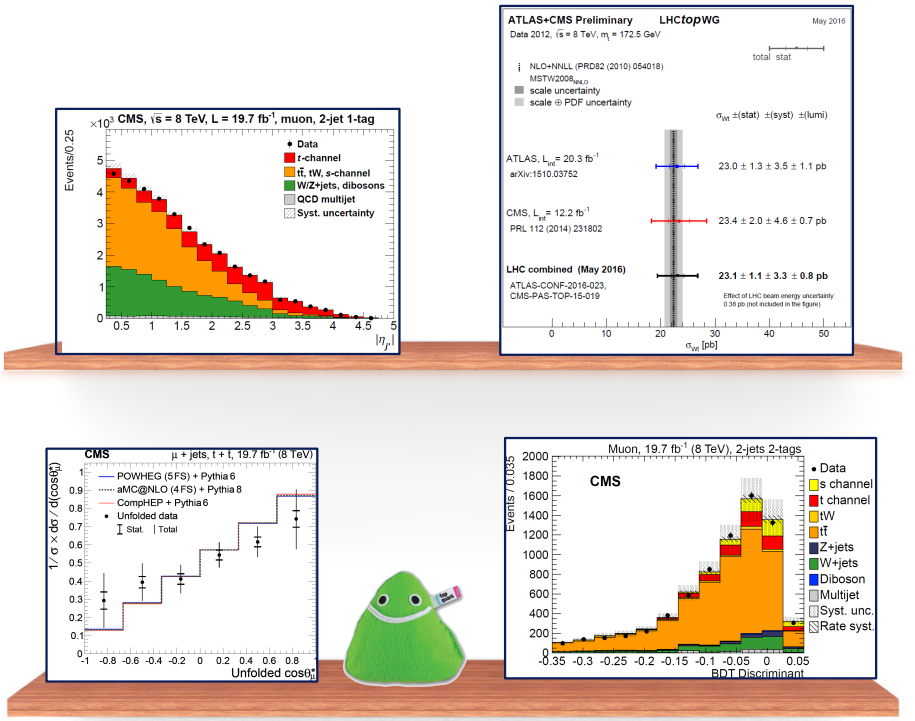
- souvenirs from LHC Run I (focus 8 TeV)
  - precise t-channel & CKM V_{tb}
  - differential t-channel
  - observation of tW
  - s-channel



- first *data hunting trophies* from LHC Run II (13 TeV)
  - inclusive t-channel cross section
  - differential t-channel cross section



Souvenirs from Run I

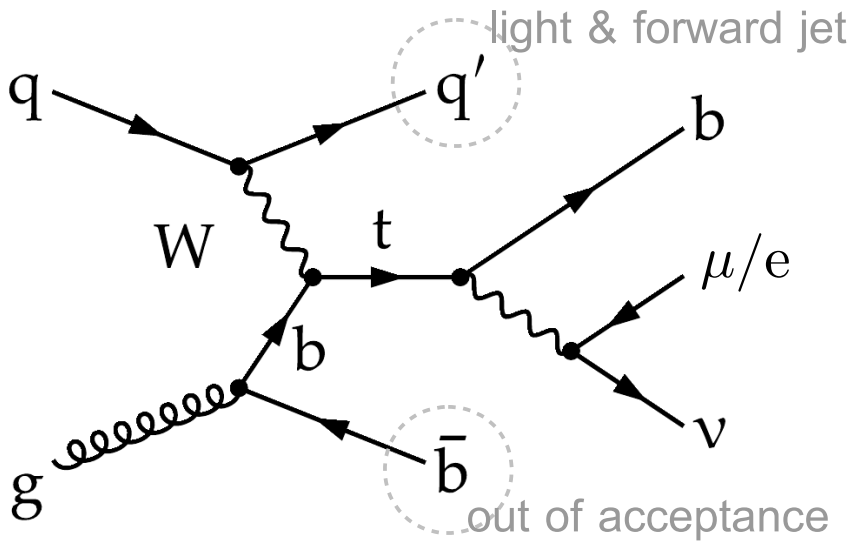


t-channel cross section @ 8 TeV

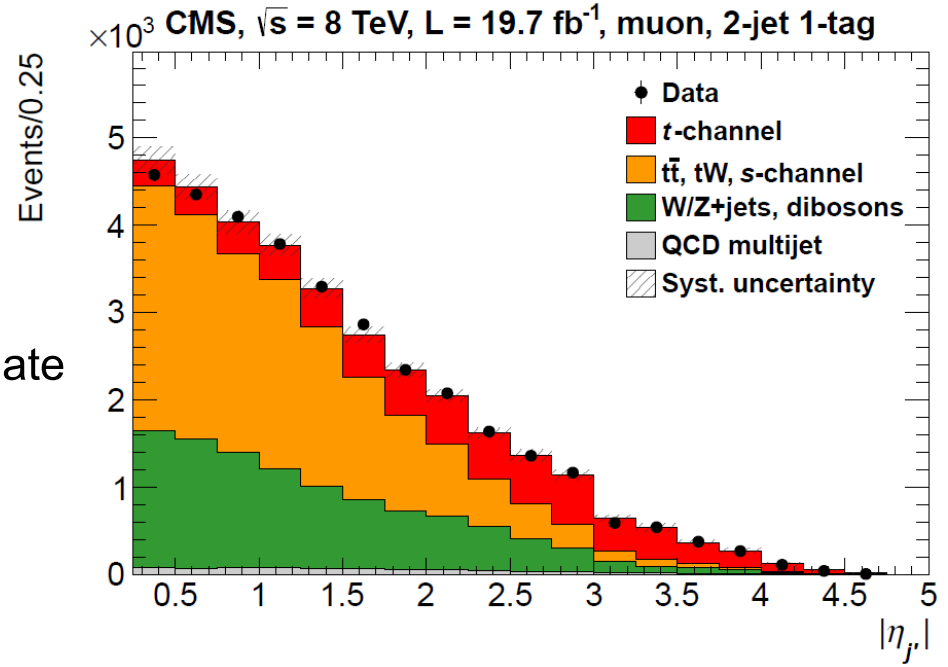
→ JHEP06 (2014) 090

- brief event selection
  - single & isolated muon $p_{\mathrm{T}} > 26\ \mathrm{GeV}, |\eta| < 2.1$ or electron $p_{\mathrm{T}} > 30\ \mathrm{GeV}, |\eta| < 2.5$
  - anti-k_{T} $R = 0.5$ jets $p_{\mathrm{T}} > 40\ \mathrm{GeV}, |\eta| < 4.5$
  - b-tagging using displaced track significance in jet $\epsilon_b \approx 46\%,\ \epsilon_{fake} \approx 0.3\%$
  - reject QCD $m_{\mathrm{T}}(\mathrm{W}) > 50\ \mathrm{GeV}$

→ signal region: 2 jets (1 b-tagged) 1 lepton, $\not{E}_{\mathrm{T}}$



- analysis strategy
  - data-driven QCD multijet background estimation
  - top quark reconstruction using neutrino candidate
  - signal extraction: binned likelihood fit to $|\eta|$ of non b-tagged jet



Neutrino candidate

(used by all presented analyses)

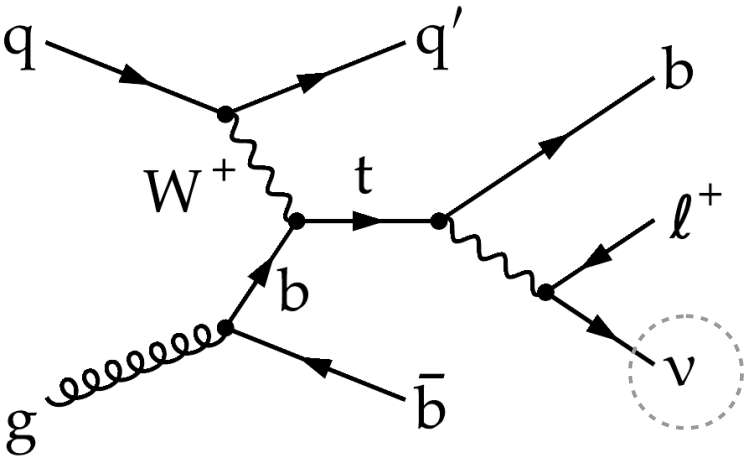
- ansatz:
  solve p_z^ν-component using W boson mass constraint

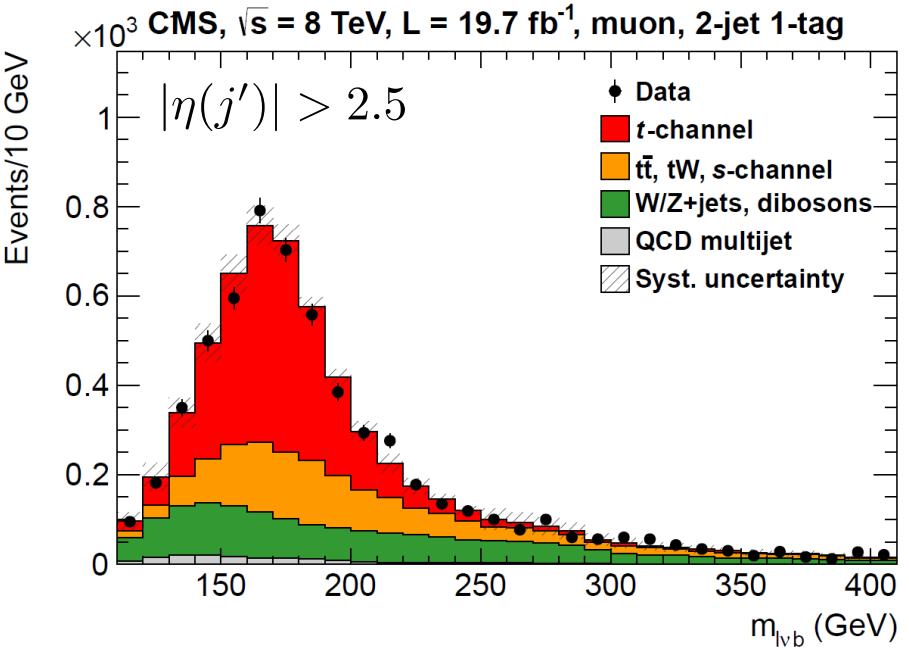
$$m_W^2 = \begin{pmatrix} E_W \\ \vec{p}_W \end{pmatrix}^2 = \left[\begin{pmatrix} E_\mu \\ \vec{p}_\mu \end{pmatrix} + \begin{pmatrix} E_\nu \\ \vec{p}_\nu \end{pmatrix} \right]^2$$

$$\Rightarrow p_{\nu,z}^{1,2} = \frac{1}{E_\mu^2 - p_{\mu,z}^2} \left[a \cdot p_{\mu,z} \pm E_\mu \sqrt{a^2 - \not{E}_T^2 (E_\mu^2 - p_{\mu,z}^2)} \right]$$

$$a = \frac{m_W^2}{2} + \not{E}_T p_T^\mu \cdot \cos(\phi_\mu - \phi_\nu)$$

  - 2 cases
    - 2 real solutions ($\frac{2}{3}$ of signal events)
      → pick smaller $|p_z^\nu|$ solution
    - complex solutions
      → set $\sqrt{a^2 - \not{E}_T^2 (E_\mu^2 - p_{\mu,z}^2)} = 0$
      → modify $p_{x,y}^\nu$





t-channel @ 8 TeV: Results

→ JHEP06 (2014) 090
→ CMS PAS TOP-15-007

cross section

$$\sigma_{t\text{-ch}} = 83.6 \pm 2.3(\text{stat.}) \pm 7.4(\text{syst.}) \text{ pb}$$
$$= 83.6 \pm 7.8 \text{ pb} \quad \left[\sigma^{\text{SM}}_{\text{t-ch.}} = 87.2 \pm 3.6 \text{ pb}\right]$$

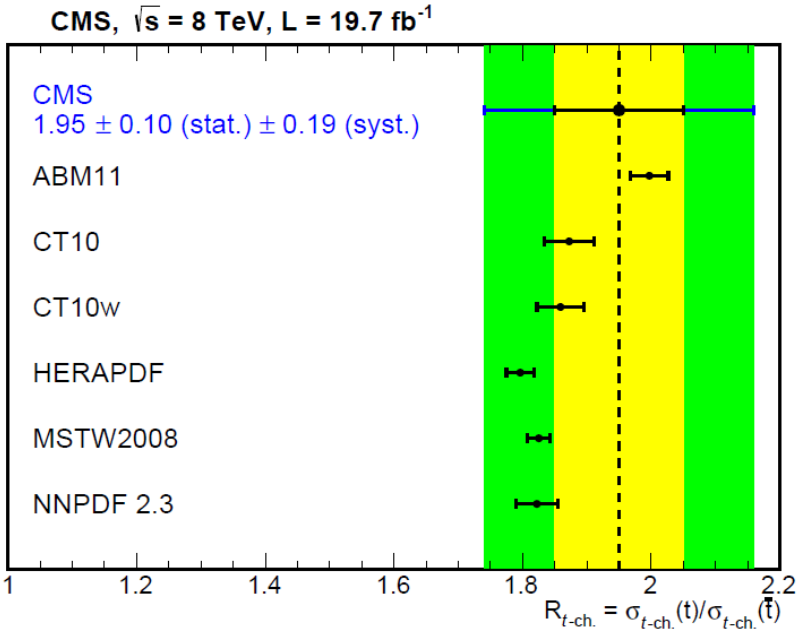
- CKM matrix element V_{tb} (7+8 TeV comb.) using $\sigma(pp \to tq) \propto V_{tb}^2$ if $V_{td},\ V_{ts} \ll V_{tb}$

$$|V_{tb}| = 0.998 \pm 0.038(\text{exp.}) \pm 0.016(\text{theo.})$$
$$|V_{tb}| > 0.92 \ @95\%\text{CL}$$

Uncertainty source	$\sigma_{t\text{-ch.}}$ (%)
Statistical uncertainty	± 2.7
JES, JER, MET, and pileup	± 4.3
b-tagging and mis-tag	± 2.5
QCD multijet estimation	± 2.3
W+jets, $t\bar{t}$ estimation	± 2.2
Signal modeling	± 5.7
PDF uncertainty	± 1.9
Luminosity	± 2.6

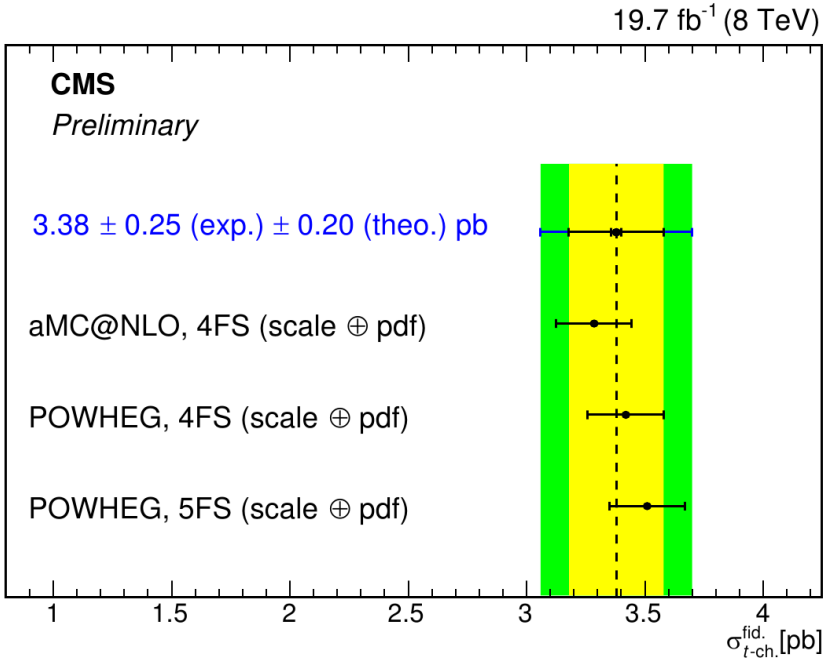
charge ratio

→ sensitive to PDFs



fiducial (= in acceptance)

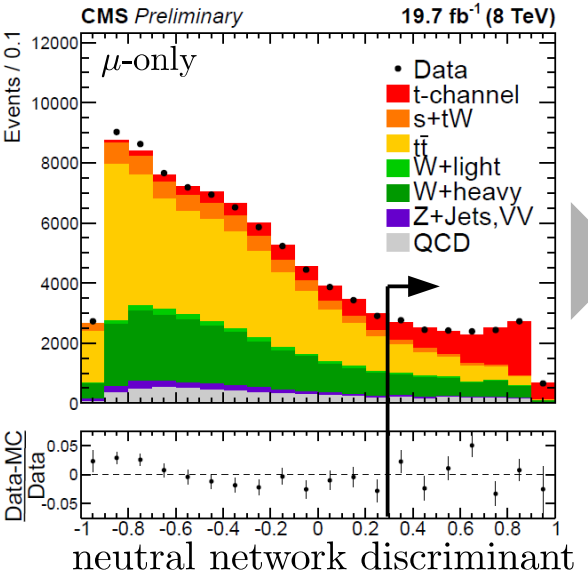
→ reduced sensitivity to theory

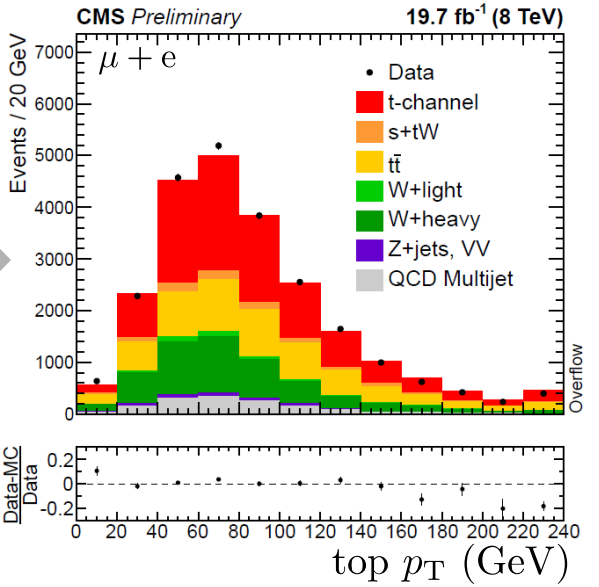


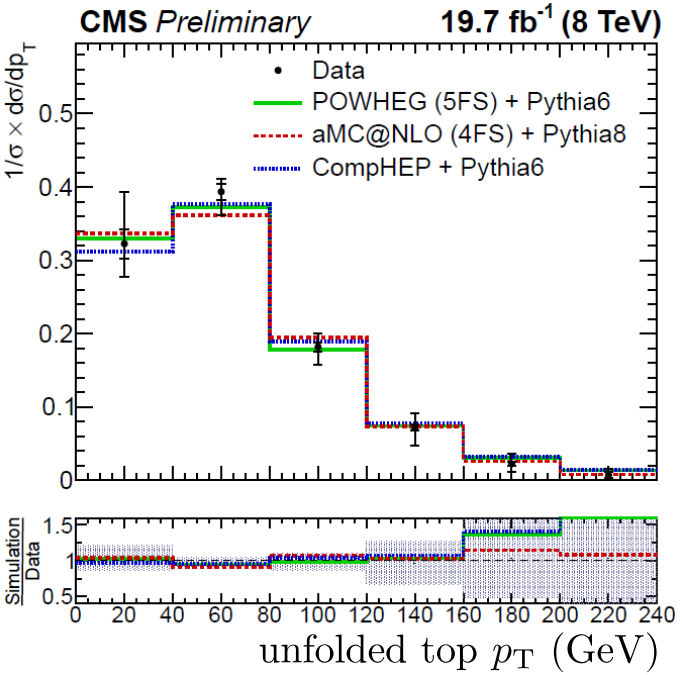
Differential t-channel @ 8 TeV

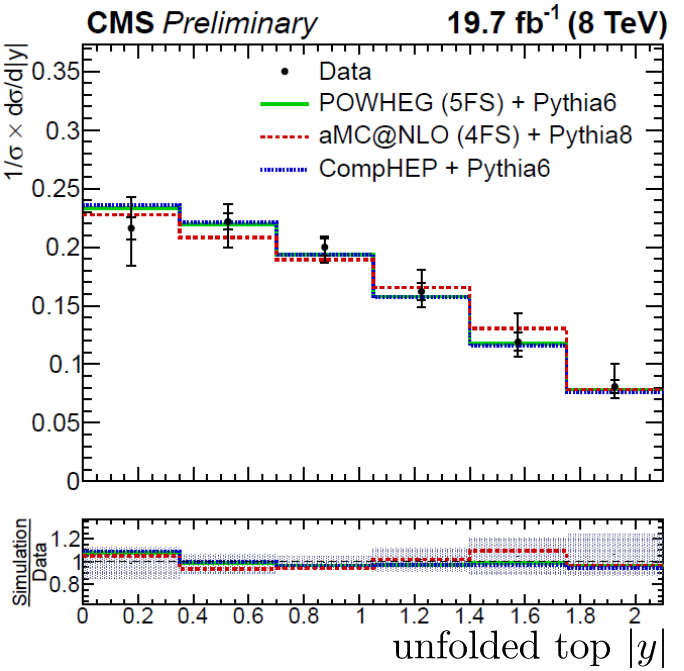
→ CMS PAS TOP-14-004

- event selection
  - similar to t-channel cross section
- analysis strategy
  - measure normalized cross section as function of top p_{T} & rapidity
  - train neural network to select data in signal-enhanced phase space
  - binned ML fit to estimate signal/background fraction in data
  - unfold to parton level
- results
  - well in agreement with generator predictions
  - measurement dominated by systematics







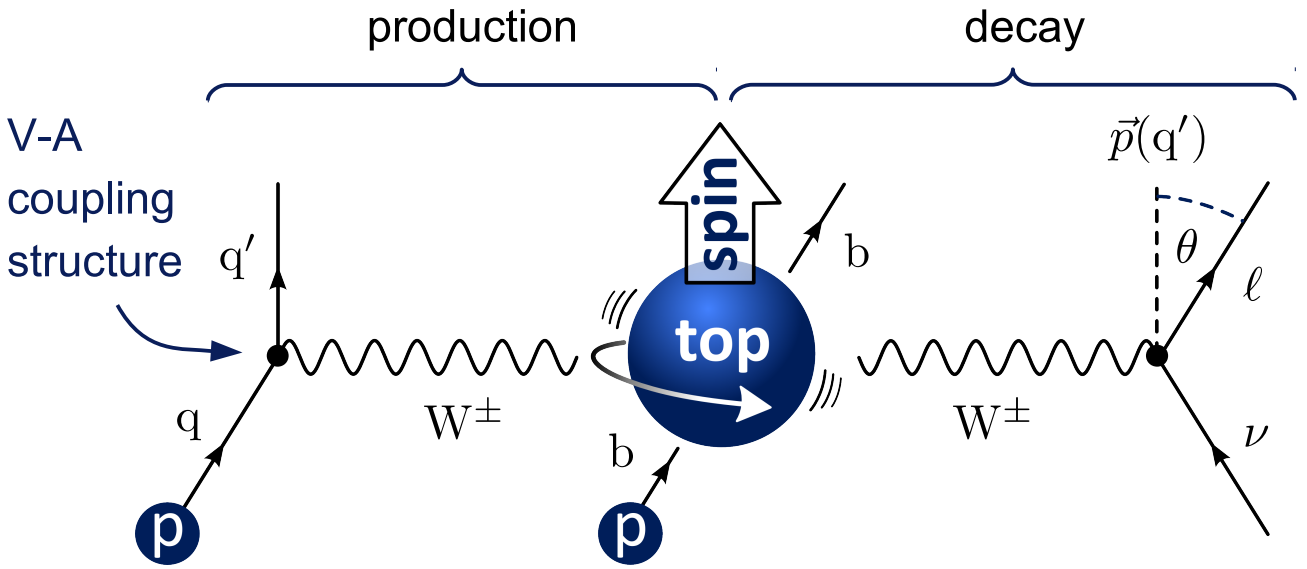


Single top polarization

→ JHEP 04 (2016) 073

NEW

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



- define polarization angle in top quark rest frame

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

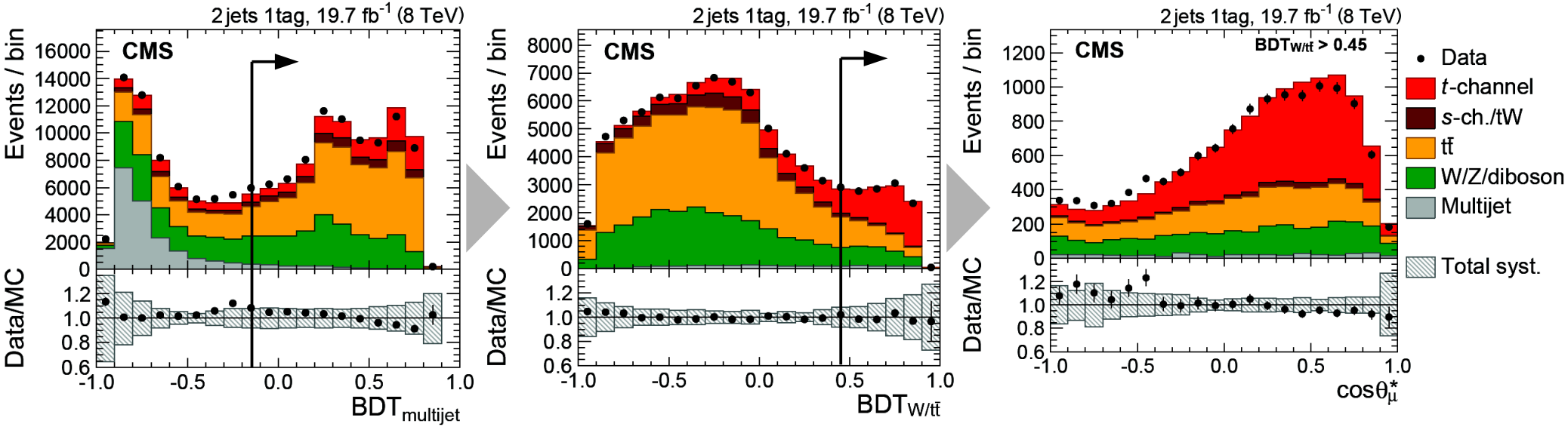
- analysis goals
  - differential cross section

$$1/\sigma \cdot \mathrm{d}\sigma/\mathrm{d}\cos\theta^{\star}$$

  - measure asymmetry

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

- analysis strategy: similar to differential t-channel cross section

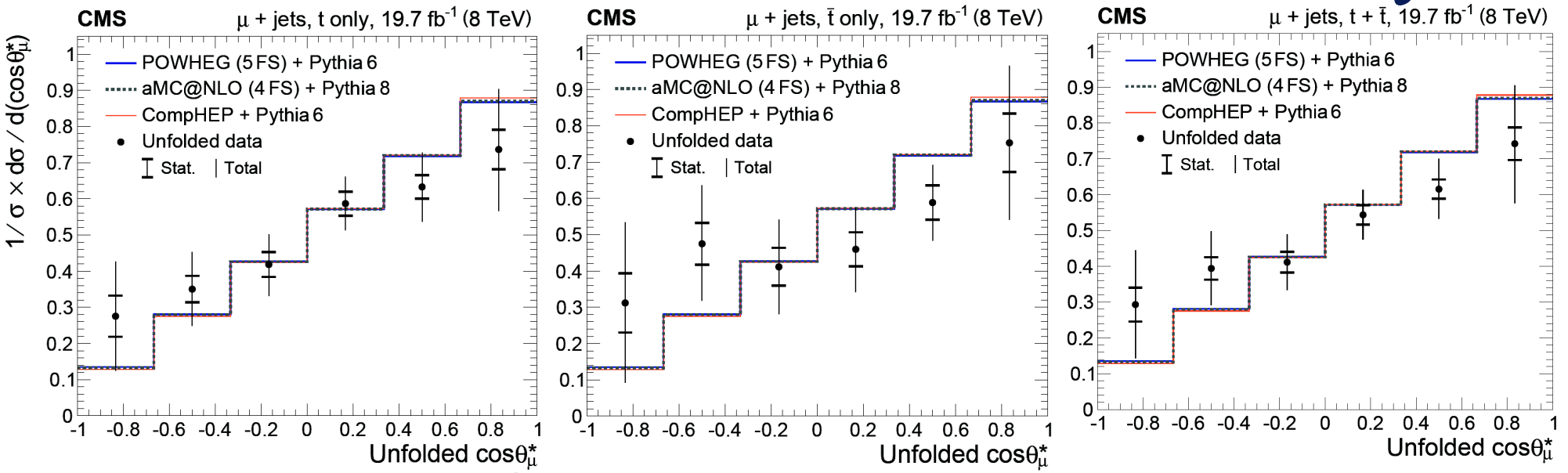


Single top polarization: Result

→ JHEP 04 (2016) 073

NEW

- differential cross section



- asymmetry
  - using linear fit (accounts for induced bin-by-bin correlations from unfolding)

$$A_\mu(\mathrm{t}) = 0.29 \pm 0.03\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}) = 0.29 \pm 0.11$$
$$A_\mu(\bar{\mathrm{t}}) = 0.21 \pm 0.05\,(\mathrm{stat}) \pm 0.13\,(\mathrm{syst}) = 0.21 \pm 0.14$$
$$A_\mu(\mathrm{t}+\bar{\mathrm{t}}) = 0.26 \pm 0.03\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}) = 0.26 \pm 0.11$$

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

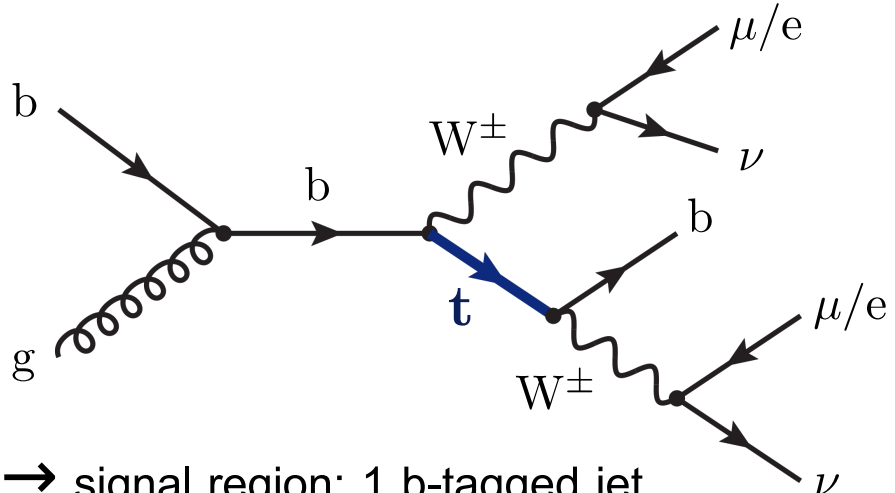
  - largest syst. uncertainties: W+jets modeling, $t\bar{t}$ modeling, jet energy/resolution calibration

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

Observation of tW @ 8 TeV

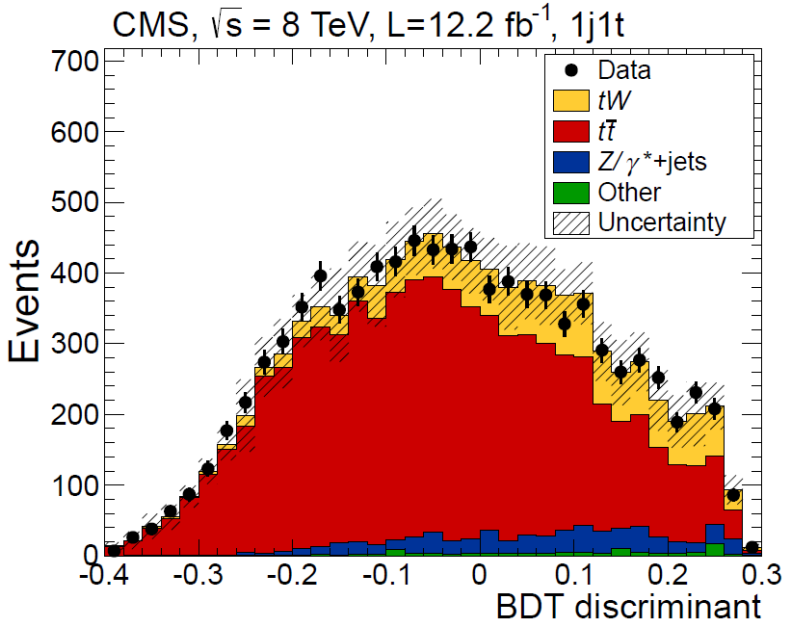
→ PRL 112 (2014)
→ CMS PAS TOP-15-019

NEW



→ signal region: 1 b-tagged jet, 2 leptons, $\not{E}_{\mathrm{T}}$

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

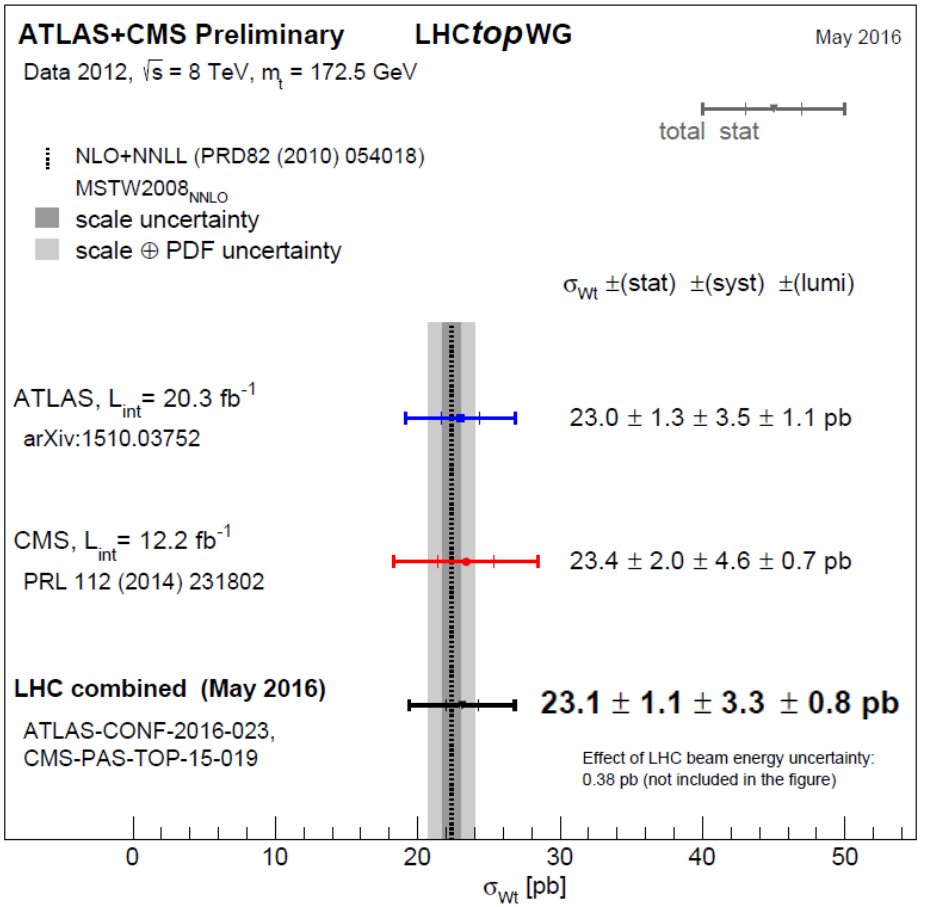


➢ result

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

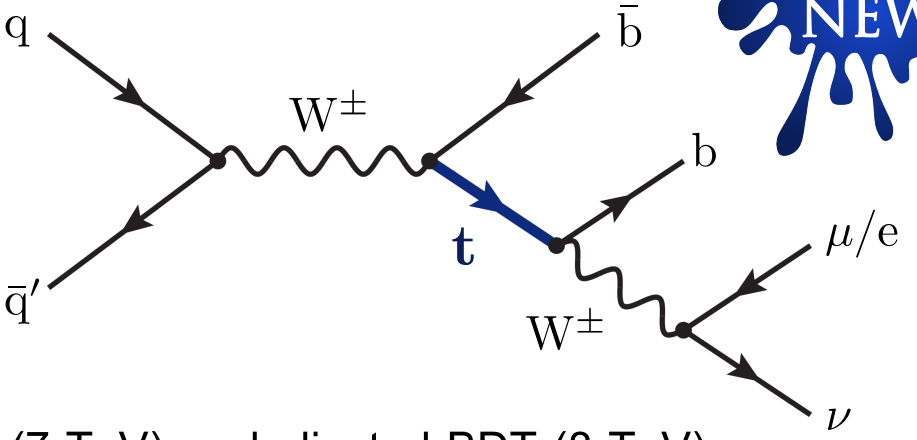
$$\left[\sigma_{\mathrm{tW}}^{(\mathrm{NLO+NNL})} = 22.6 \pm 1.5 \text{ pb}\right]$$

➢ legacy 8 TeV combination with ATLAS

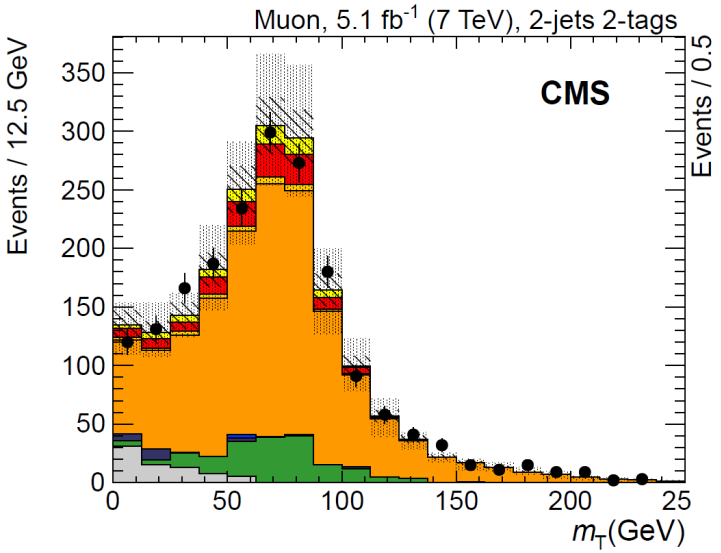


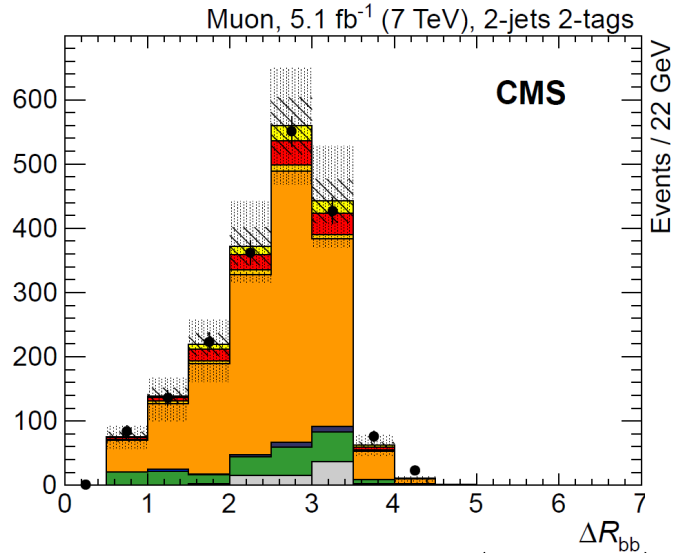
s-channel at 7 & 8 TeV

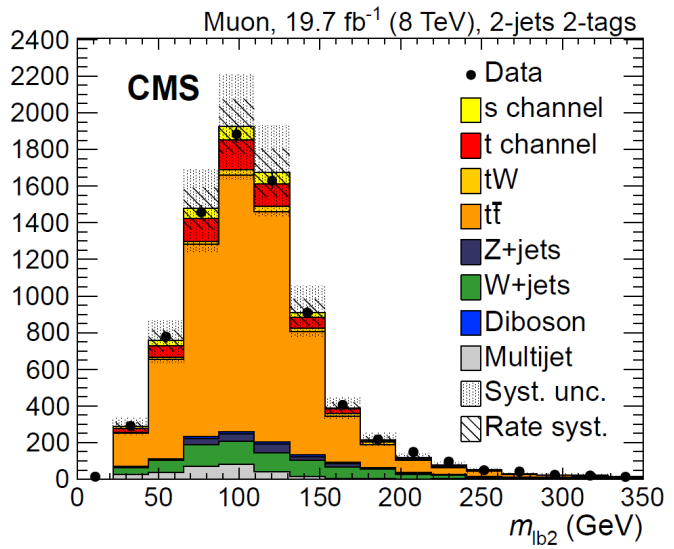
→ arXiv:1603.02555
(submitted to JHEP)



- signal region
  - 2 jets (both b-tagged), 1 isolated μ/e, $\not{E}_T$
- analysis strategy
  - BDTs trained to separated signal from overwhelming $t\bar{t}$ & W+jets
  - data-driven estimation of QCD using $m_T(W)$ (7 TeV) or dedicated BDT (8 TeV)
  - top quark candidate uses b-tagged jet yielding $\min|m_{b\ell\nu} - 172.5\ \text{GeV}|$
  - cross section estimated by performing a simultaneous ML fit to BDT distribution in signal & control regions (2j1t, 3j2t)
- most discriminating variables







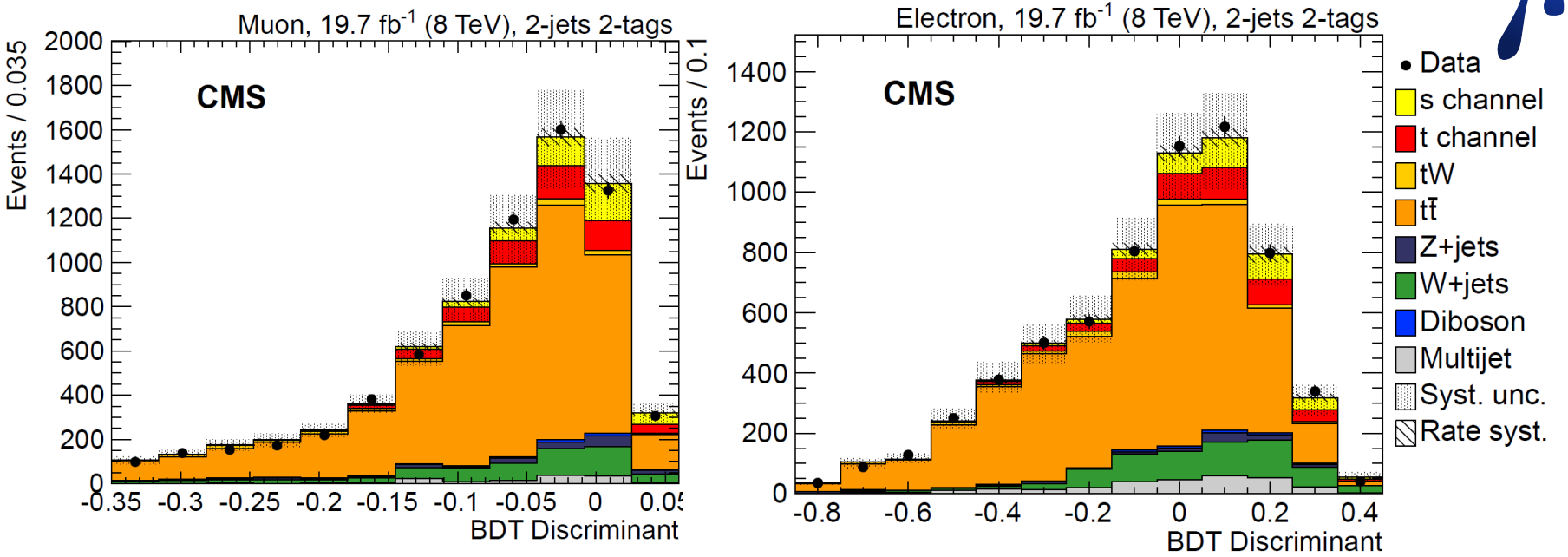
- others: dijet p_T, $\Delta\phi(t, b_1)$, $\Delta\phi(t, b_2)$, $m_{b\ell\nu}$, H_T, $\cos\theta(\ell, \text{beam})$, $\not{E}_T$, $p_T(\ell)$

s-channel: Result

→ arXiv:1603.02555
(submitted to JHEP)

NEW

- BDTs at 8 TeV

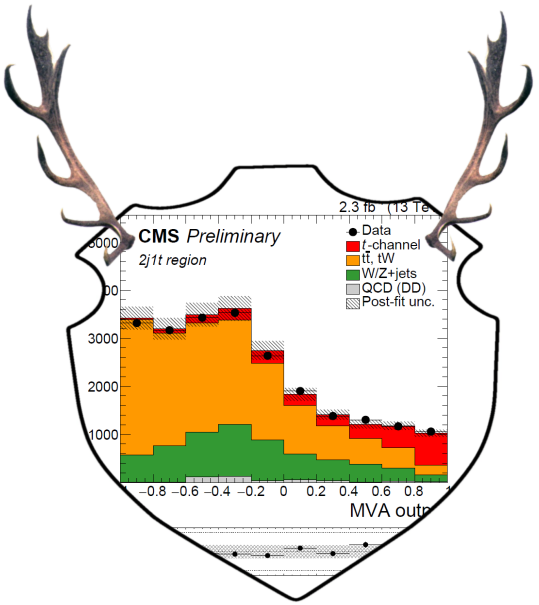


- measurement
  - cross sections per energy

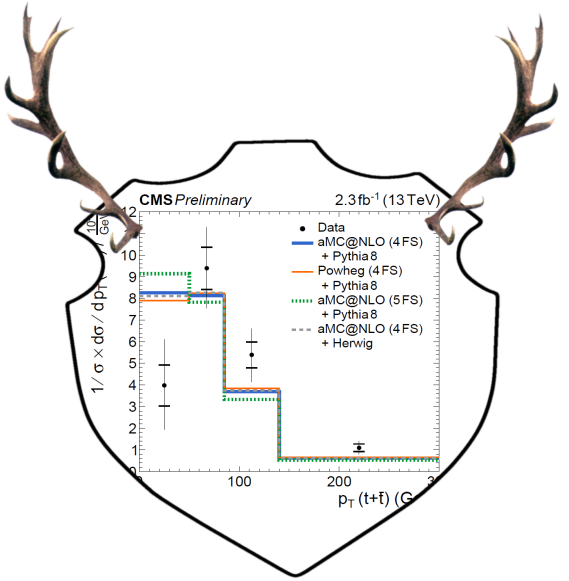
$$\sigma_{s\text{-ch.}}^{\mu,7\ \mathrm{TeV}} = 7.1 \pm 34\%(\mathrm{stat.}) \pm 110\%(\mathrm{syst.})\ \mathrm{pb} \qquad \left[\sigma_{s\text{-ch.}}^{\mathrm{SM},7\ \mathrm{TeV}} = 4.6 \pm 0.2\ \mathrm{pb}\right]$$

$$\sigma_{s\text{-ch.}}^{\mu+\mathrm{e},8\ \mathrm{TeV}} = 13.4 \pm 10\%(\mathrm{stat.}) \pm 54\%(\mathrm{syst.})\ \mathrm{pb} \qquad \left[\sigma_{s\text{-ch.}}^{\mathrm{SM},8\ \mathrm{TeV}} = 5.6 \pm 0.2\ \mathrm{pb}\right]$$

  - largest systematic uncertainties: jet calibration (66%, 34%), Q scale (54%, 30%), b-tagging efficiency (34%, 14%)
  - combined signal strength: $\frac{\sigma_{\mathrm{meas.}}}{\sigma_{\mathrm{theo.}}} \equiv \beta_{\mathrm{signal}} = 2.0 \pm 0.9$



First trophies from Run II



Inclusive t-channel cross section

→ CMS-PAS-TOP-16-003

NEW

- event selection

  - certified data $\int L = 2.3\ \mathrm{fb}^{-1}$
    (all subdetectors operational
    & nominal mag. field of 4T)

  - isolated muon trigger

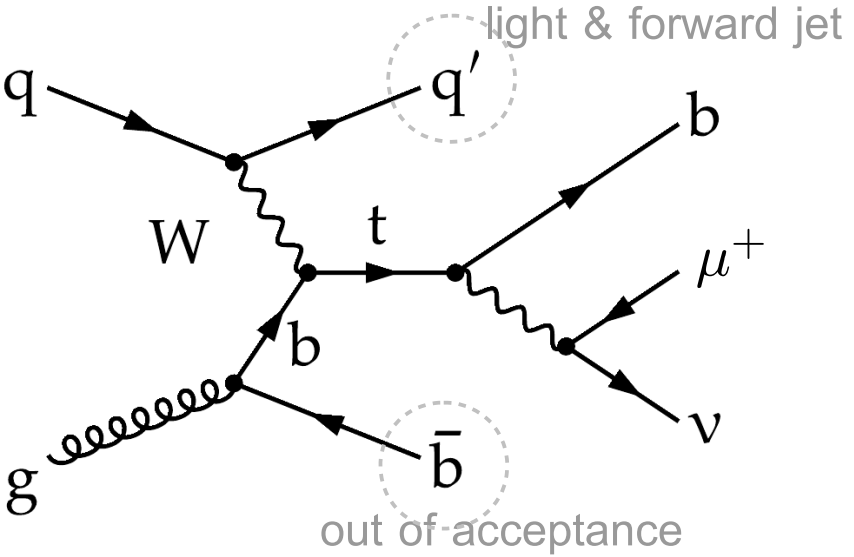
  - 1 well isolated muon $p_{\mathrm{T}} > 22\ \mathrm{GeV},\ |\eta| < 2.1$

  - veto additional loosely isolated leptons
    - muons $p_{\mathrm{T}} > 10\ \mathrm{GeV},\ |\eta| < 2.5$
    - electrons $p_{\mathrm{T}} > 20\ \mathrm{GeV},\ |\eta| < 2.5$

  - anti-k_{T} jets $p_{\mathrm{T}} > 40\ \mathrm{GeV},\ |\eta| < 4.7$

  - b-tagging using MVA discriminant
    - $\epsilon_b \approx 45\%,\ \epsilon_{fake} \approx 0.1\%$

  - reject multijet events from QCD
    $m_{\mathrm{T}}(\mathrm{W}) > 50\ \mathrm{GeV}$



define signal & control regions
- 2 jets & 0 b-tags: W+jets
- 2 jets & 1 b-tag: signal
- 3 jets & 1, 2 b-tags: $t\bar{t}$

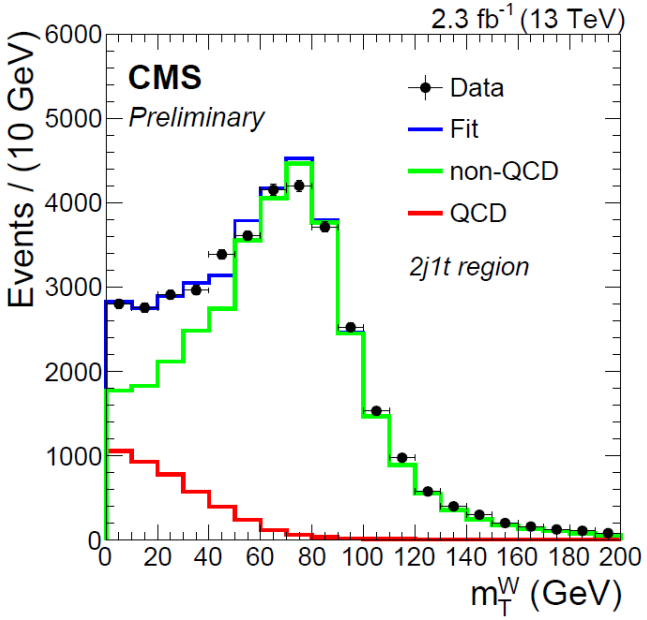
Signal extraction

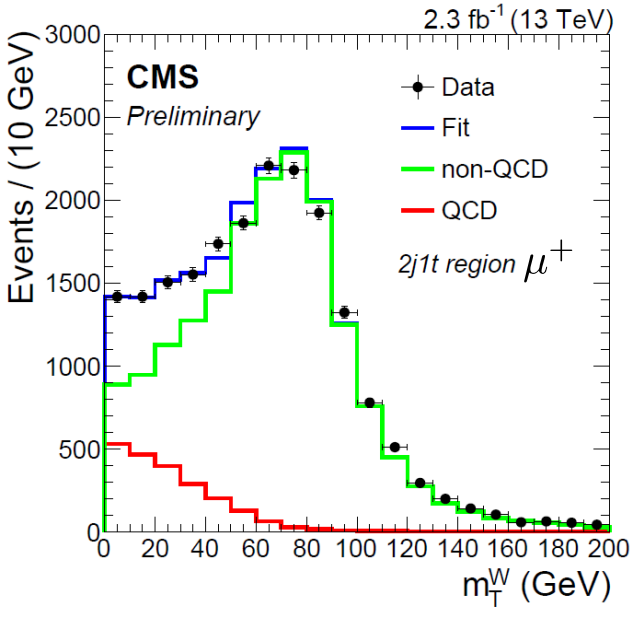
→ CMS-PAS-TOP-16-003

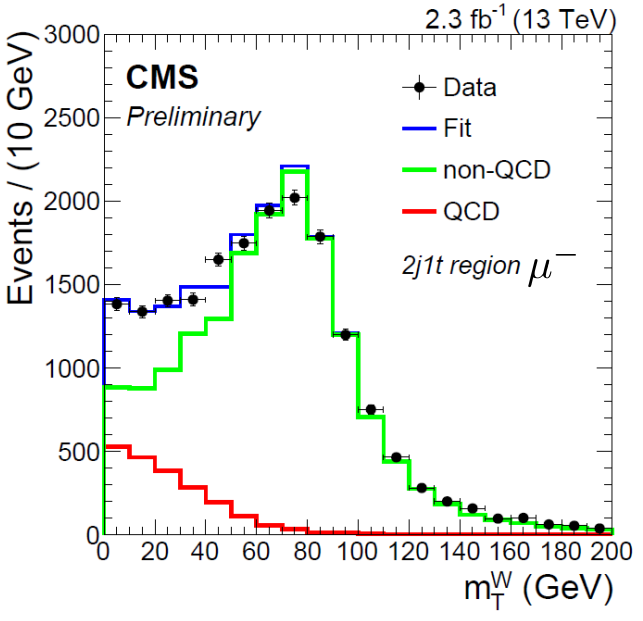
NEW

- 2 staged binned maximum likelihood fits
  - **QCD** estimated with 2 component ML fit to $m_{\mathrm{T}}(\mathrm{W})$ distribution
  - data-driven QCD template using data events with **antiisolated muons**

inclusive | separately by charge







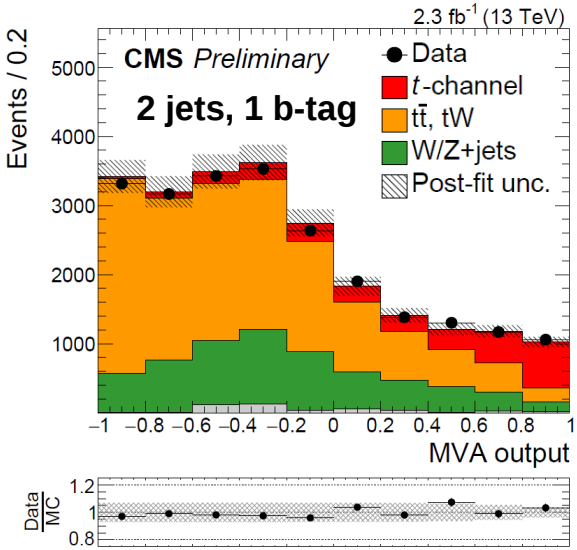
  - **signal & W+jet, $\mathrm{t\bar{t}}$ background** estimated using **neural network** discriminant
  - 11 input variables (ordered by decreasing importance):
    $|\eta(j')|$, reconstructed top quark mass, dijet mass, $m_{\mathrm{T}}(\mathrm{W})$ $\sum p_{\mathrm{T}}^{\mathrm{jet}}$
    top quark polarization angle $\cos\theta^{\star}$, leading jet mass, $\Delta R(j',\ \mathrm{b})$,
    $p_{\mathrm{T}}(j')$, $m(j')$, $|\eta(\mathrm{W})|$

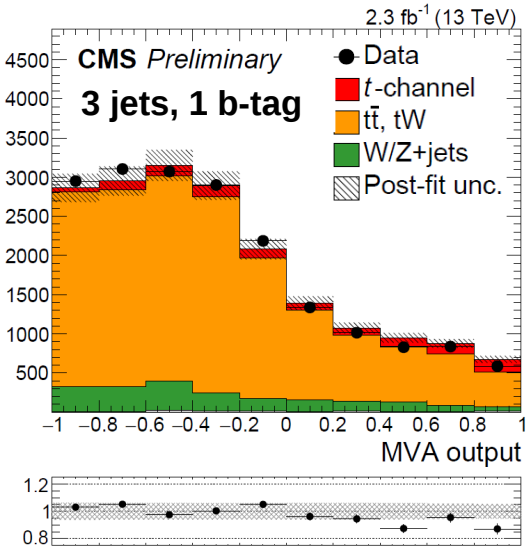
Signal extraction (2)

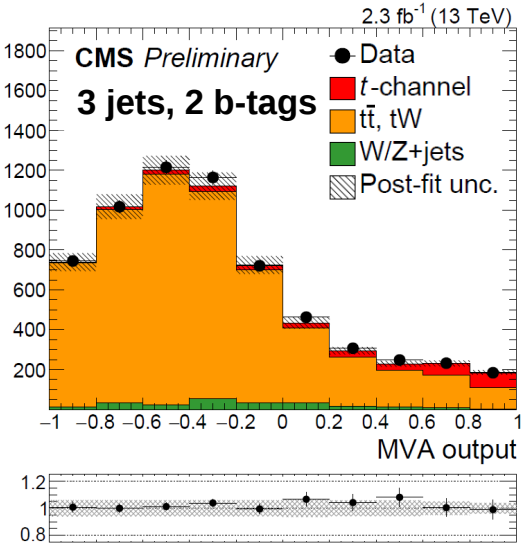
→ CMS-PAS-TOP-16-003

NEW

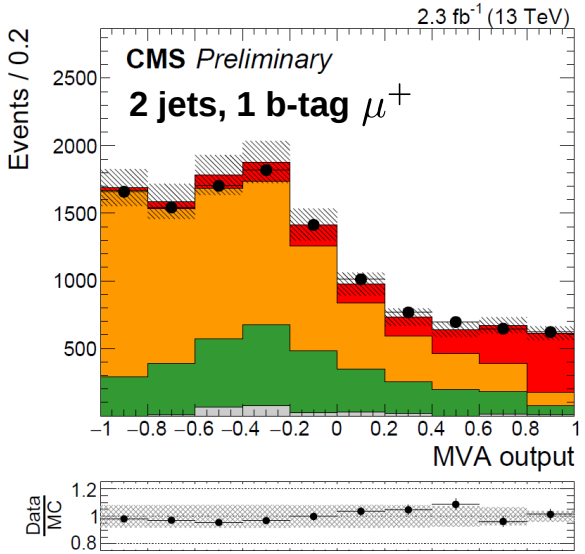
- simultaneously fit NN discriminant in signal region and both $t\bar{t}$ control regions
  → reduces correlation between estimated W+jets vs. $t\bar{t}$ background yields
- inclusive (scaled to fit result)

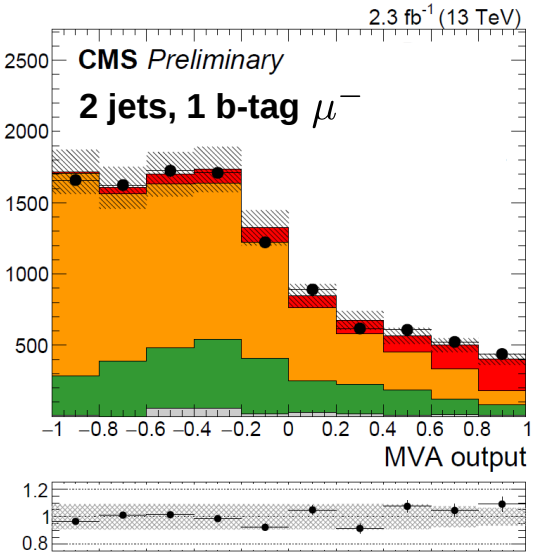






- separately by charge (scaled to fit result)





→ data well modeled by simulation

Statistical evaluation

→ CMS-PAS-TOP-16-003

- experimental uncertainties
  - constrained in the ML fit by introducing additional nuisance parameters
  - each nuisance parameter corresponds to a systematic uncertainty controlling yield & shape of fit templates
- theoretical uncertainties
  - individual fits using shifted templates per uncertainty
- result

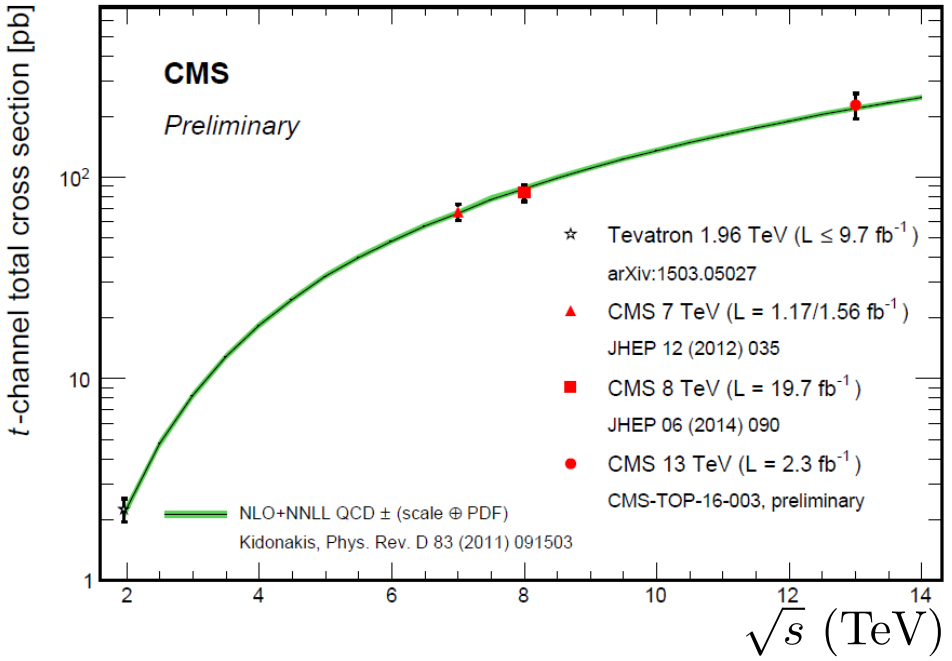
uncertainty source	$\Delta\sigma_{t-\text{ch.},t+\bar{t}}/\sigma^{\text{obs}}_{t-\text{ch.},t+\bar{t}}$	$\Delta\sigma_{t-\text{ch.},t}/\sigma^{\text{obs}}_{t-\text{ch.},t}$	$\Delta\sigma_{t-\text{ch.},\bar{t}}/\sigma^{\text{obs}}_{t-\text{ch.},\bar{t}}$
statistical uncertainty	±4.0%	±4.7%	±7.6%
profiled uncertainties	±5.5%	±5.7%	±9.2%
MC statistics	±2.8%	±3.4%	±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	±7.9%	±10.1%	±8.2%
$t\bar{t}$ modeling	±4.3%	±3.9%	±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	±0.1%	±0.1%	±0.2%
total theory uncertainties	-12.1/+12.6	-13.8/+13.6	-13.5/+13.4%
luminosity	±2.7%	±2.7%	±2.7%
total uncertainty	-14.5/+14.8%	-16.3/+16.1%	-18.6/+18.6%
total uncertainty	-14.5/+14.8%	-16.3/+16.1%	-18.6/+18.6%

→ experimental uncertainties small compared to impact of theoretical uncertainties

→ largest single uncertainty from signal modeling (aMC@NLO ↔ Powheg)

Results

→ CMS-PAS-TOP-16-003



- measured cross sections

$$\sigma(t) = 141 \pm 5\%\ (\text{stat.}) \pm \ \ 7\%\ (\text{exp.}) \pm 14\%\ (\text{theo.}) \pm 3\%\ (\text{lumi.})\ \text{pb}$$

$$\sigma(\bar{t}) = \ \ 81 \pm 8\%\ (\text{stat.}) \pm 10\%\ (\text{exp.}) \pm 13\%\ (\text{theo.}) \pm 3\%\ (\text{lumi.})\ \text{pb}$$

$$\sigma(t+\bar{t}) = 228 \pm 4\%\ (\text{stat.}) \pm \ 6\%\ (\text{exp.}) \pm 12\%\ (\text{theo.}) \ \pm 3\%\ (\text{lumi.})\ \text{pb}$$

$$= 228 \pm 15\%\ \text{pb} \qquad \left[\sigma^{\text{SM}} = 217^{+9}_{-8}\ \text{pb}\right]$$

- CKM matrix element V_{tb} assuming $|V_{tb}| \gg |V_{td}|,\ |V_{ts}|$

$$|f_{LV} V_{tb}| = 1.02 \pm 0.07\ (\text{exp.}) \pm 0.02\ (\text{theo.})$$

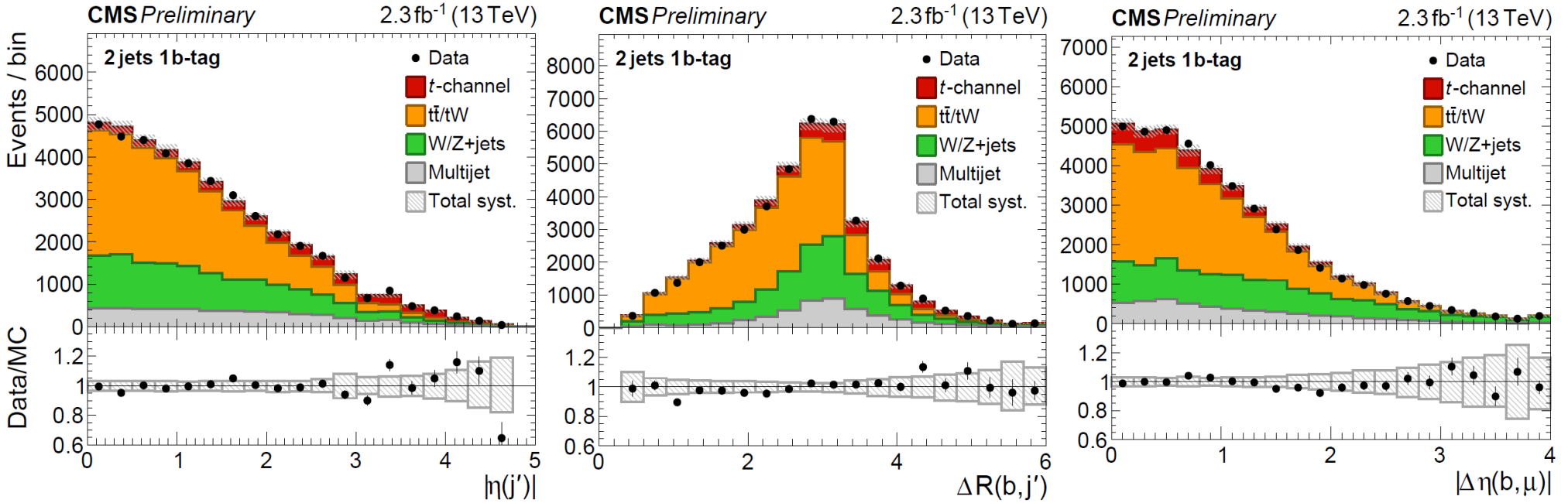
Differential t-channel @ 13 TeV

→ CMS-PAS-TOP-16-004

NEW

- goal: 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 ML fits to $m_{\mathrm{T}}(\mathrm{W})$ & Boosted Decision Tree discriminant per bin
  - use fit results to unfold to parton level

- train BDT to separate signal from W+jets, $t\bar{t}$ & QCD background
  - 5 input variables (uncorrelated to top quark p_{T}, $|y|$)
    $|\eta(j')|$, reconstructed top quark mass, $m_{\mathrm{T}}(\mathrm{W})$ $\Delta R(b, j')$ $|\Delta\eta(b, \mu)|$



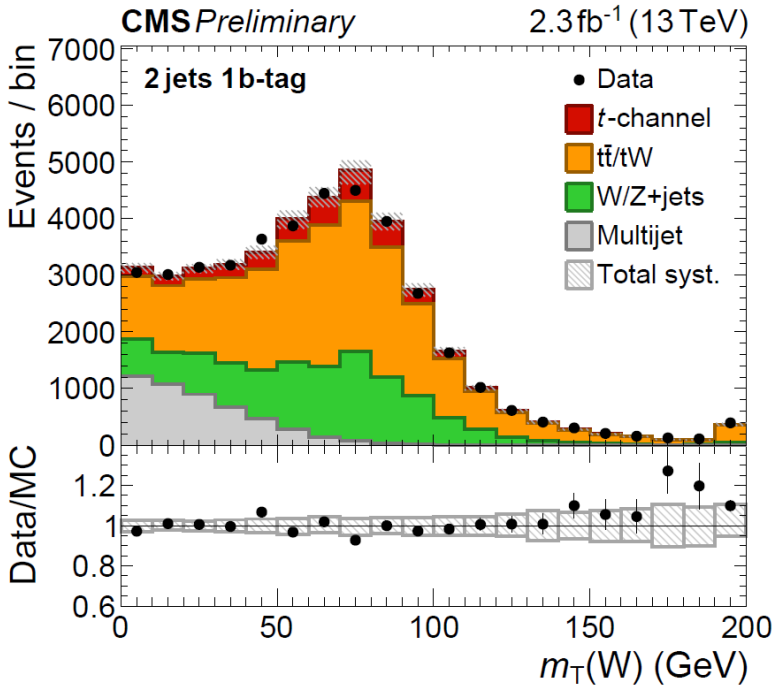
→ data well modeled by simulation

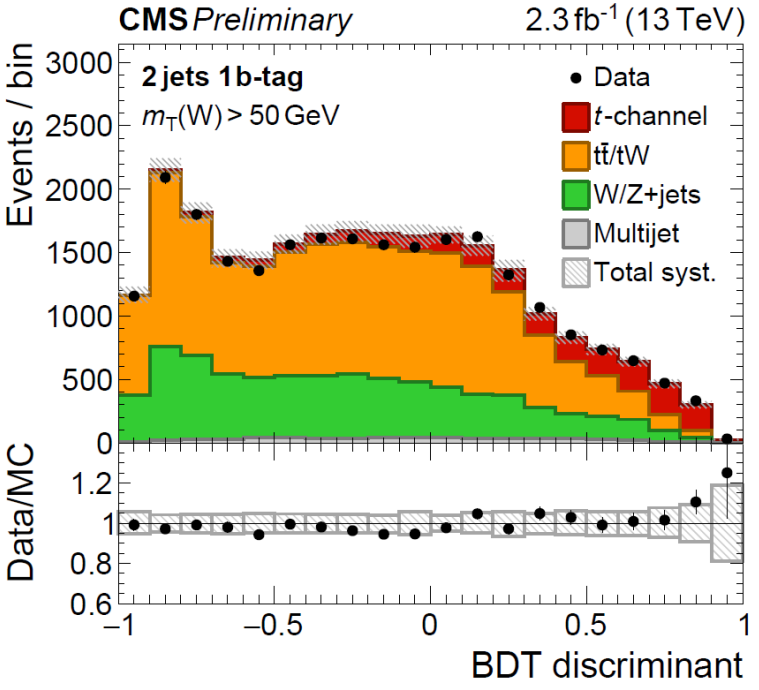
Signal extraction

→ CMS-PAS-TOP-16-004

NEW

- perform only one ML fit to estimate signal & background composition in data
  - data-driven QCD template from data events with antiisolated muons
  - construct extended likelihood using $m_{\mathrm{T}}(\mathrm{W})$ & BDT distribution





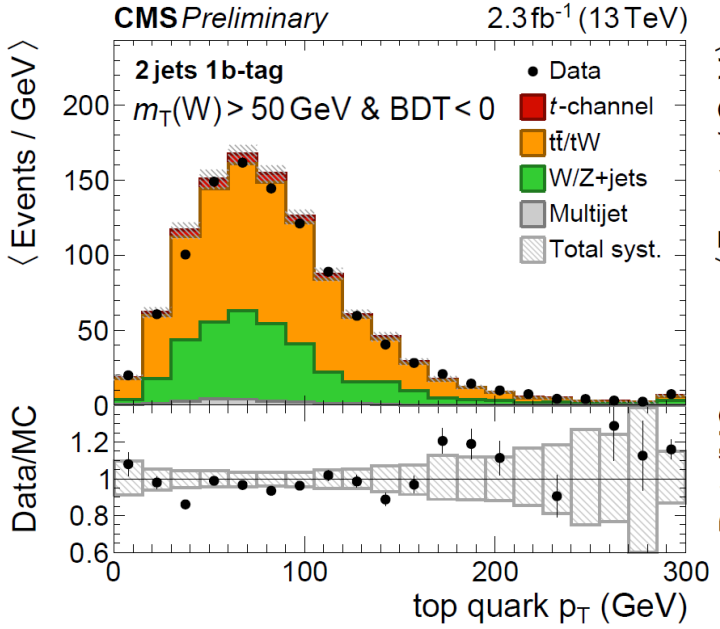
$$\Rightarrow L = L(m_{\mathrm{T}}(\mathrm{W})|m_{\mathrm{T}}(\mathrm{W}) < 50\ \mathrm{GeV}) \cdot L(\mathrm{BDT}|m_{\mathrm{T}}(\mathrm{W}) > 50\ \mathrm{GeV})$$

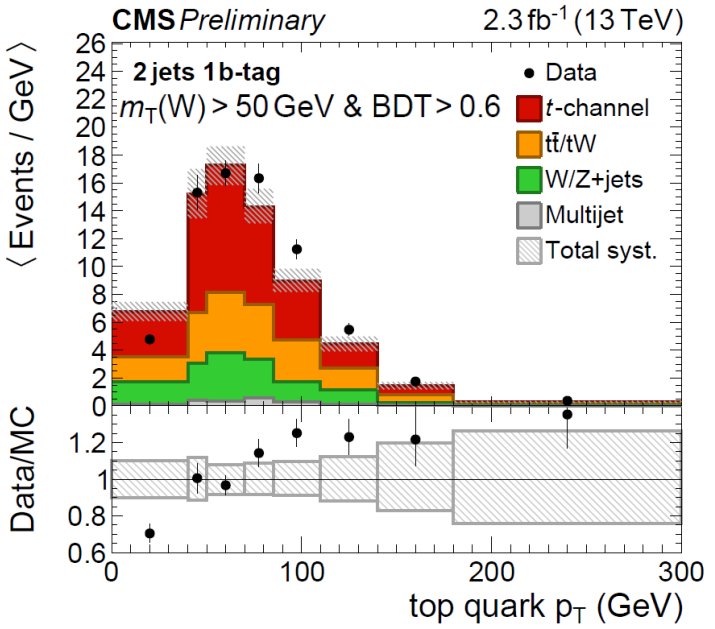
- $t\bar{t}$ control regions fitted simultaneously to reduce correlations (QCD yield independent per region)

Validation

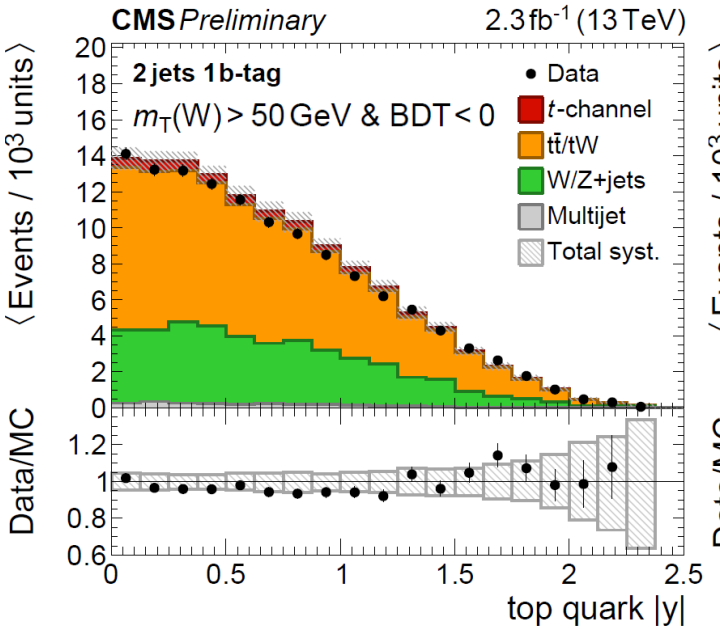
→ CMS-PAS-TOP-16-004

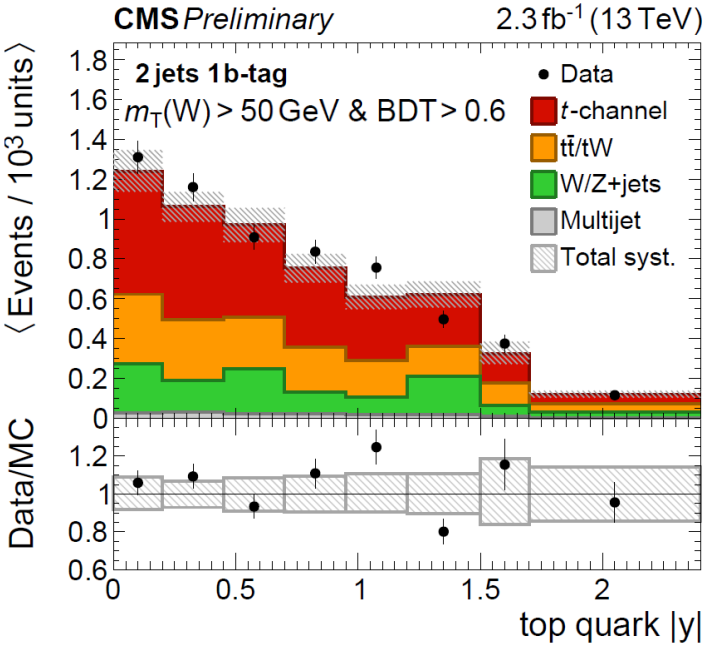
➢ modeling in signal-depleted & signal-enhanced regions using additional BDT selection





- signal-depleted region well modeled by simulation
- data display slightly harder p_{T} spectrum than simulation for signal





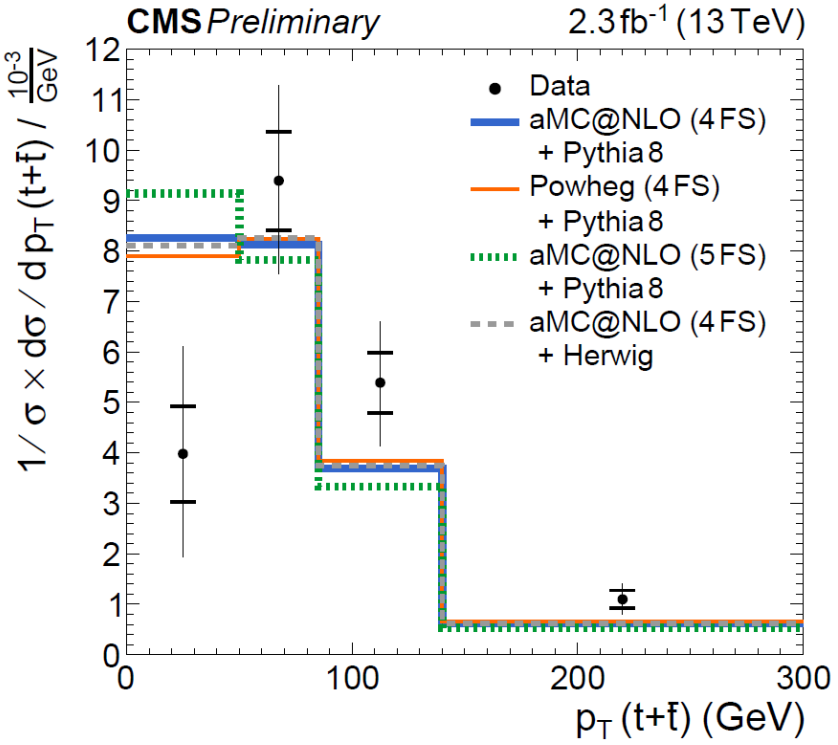
- rapidity well described in both regions

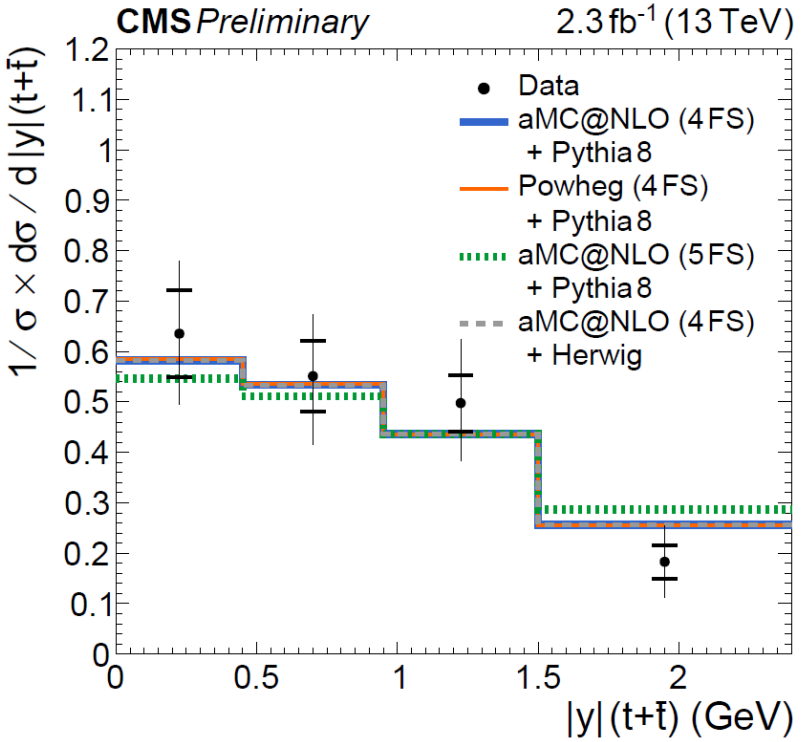
Result

→ CMS-PAS-TOP-16-004

NEW

- measured normalized differential cross sections





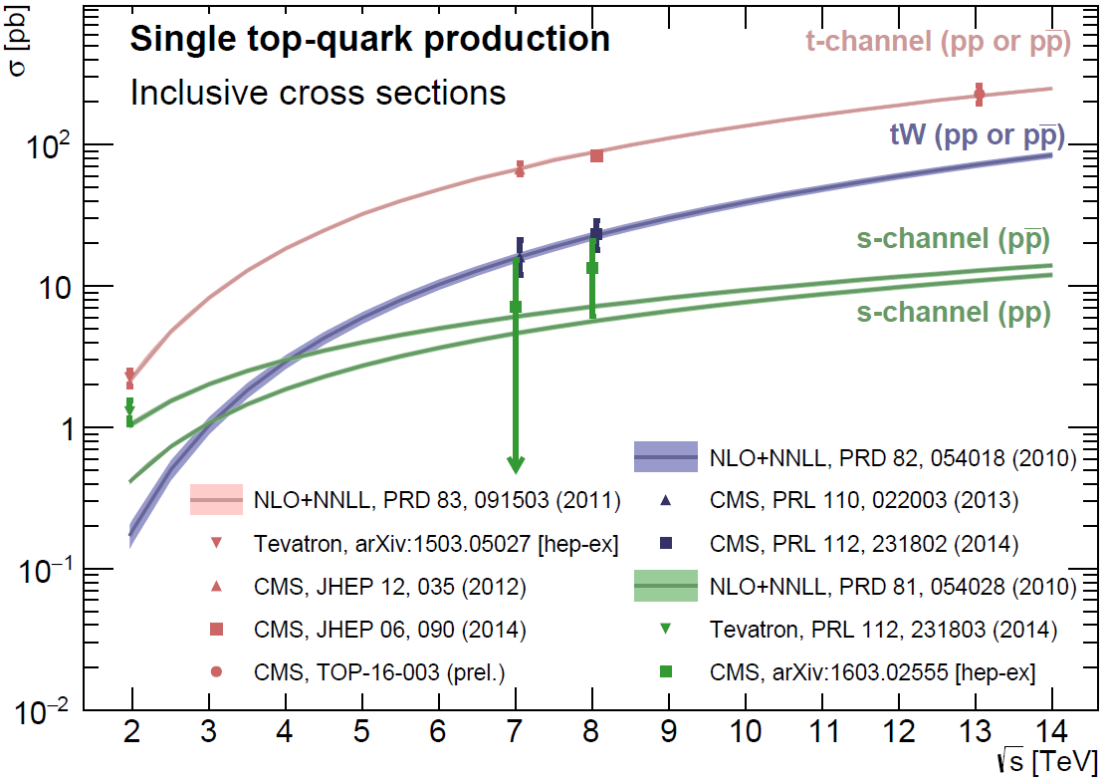
→ data described by theoretical predictions within the relatively large uncertainties

→ large rel. uncertainty in first p_{T} bin due to low acceptance & high sensitivity to systematic uncertainties

- largest uncertainties
  - data statistics (10% – 25%), Q scale (10% – 15%), top quark mass (10% – 20%), jet energy corrections (10% – 15%)

Summary

- souvenirs from Run I
  - precise t-channel & V_{tb}
  - differential t-channel
    - as a function of top quark p_T & rapidity & polarization angle
  - tW observation & legacy combination
  - s-channel



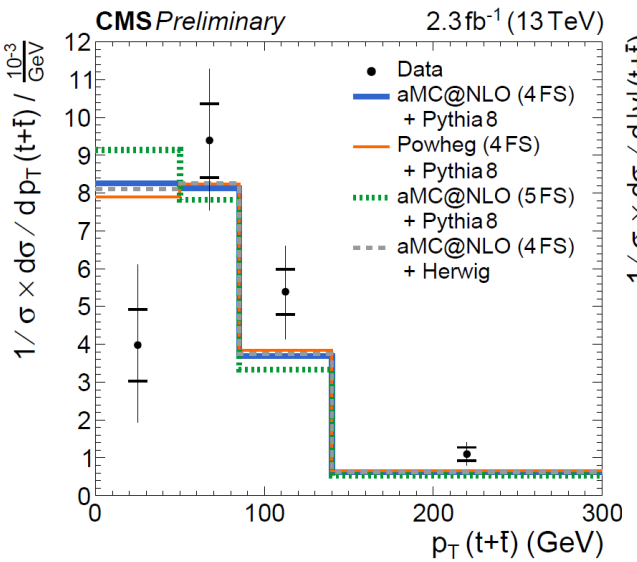
- first trophies from Run II
  - inclusive single top t-channel cross section

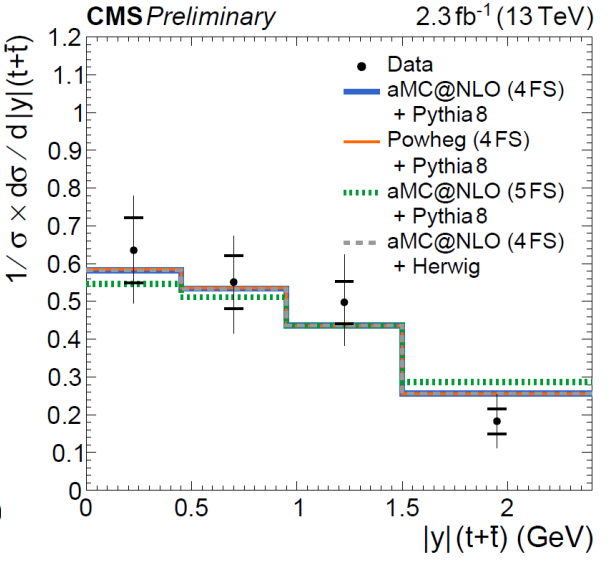
    $\sigma^{13\ \mathrm{TeV}}_{t\text{-ch.}} = 228 \pm 15\%\ \mathrm{pb}$

    currently most precise @ 13 TeV

    $\sigma^{13\ \mathrm{TeV}}_{t\text{-ch.,ATLAS}} = 229 \pm 21\%\ \mathrm{pb}$

    → ATLAS-CONF-2015-079
  - differential t-channel cross section





Backup

t-channel @ 8 TeV

- Systematic uncertainties

Uncertainty source	$\sigma_{t\text{-ch.}}$ (%)
Statistical uncertainty	$\pm$ 2.7
JES, JER, MET, and pileup	$\pm$ 4.3
b-tagging and mis-tag	$\pm$ 2.5
Lepton reconstruction/trig.	$\pm$ 0.6
QCD multijet estimation	$\pm$ 2.3
W+jets, $t\bar{t}$ estimation	$\pm$ 2.2
Other backgrounds ratio	$\pm$ 0.3
Signal modeling	$\pm$ 5.7
PDF uncertainty	$\pm$ 1.9
Simulation sample size	$\pm$ 0.7
Luminosity	$\pm$ 2.6
Total systematic	$\pm$ 8.9
Total uncertainty	$\pm$ 9.3
Measured cross section	83.6 $\pm$ 7.8 pb

Uncertainty source	$\sigma_{t\text{-ch.}}(t)$ (%)	$\sigma_{t\text{-ch.}}(\bar{t})$ (%)	$R_{t\text{-ch.}}$ (%)
Statistical uncertainty	$\pm$ 2.7	$\pm$ 4.9	$\pm$ 5.1
JES, JER, MET, and pileup	$\pm$ 4.2	$\pm$ 5.2	$\pm$ 1.1
b-tagging and mis-tag	$\pm$ 2.6	$\pm$ 2.6	$\pm$ 0.2
Lepton reconstruction/trig.	$\pm$ 0.5	$\pm$ 0.5	$\pm$0.3
QCD multijet estimation	$\pm$ 1.6	$\pm$ 3.5	$\pm$1.9
W+jets, $t\bar{t}$ estimation	$\pm$ 1.7	$\pm$ 3.6	$\pm$ 3.0
Other backgrounds ratio	$\pm$ 0.1	$\pm$ 0.2	$\pm$ 0.6
Signal modeling	$\pm$ 4.9	$\pm$ 9.4	$\pm$ 6.1
PDF uncertainty	$\pm$ 2.5	$\pm$ 4.8	$\pm$ 6.2
Simulation sample size	$\pm$ 0.6	$\pm$ 1.1	$\pm$ 1.2
Luminosity	$\pm$ 2.6	$\pm$ 2.6	—
Total systematic	$\pm$ 8.2	$\pm$ 13.4	$\pm$ 9.6
Total uncertainty	$\pm$ 8.7	$\pm$ 14.2	$\pm$ 10.9
Measured cross section or ratio	53.8 $\pm$ 4.7 pb	27.6 $\pm$ 3.9 pb	1.95 $\pm$ 0.21

- definition of fiducial phase space

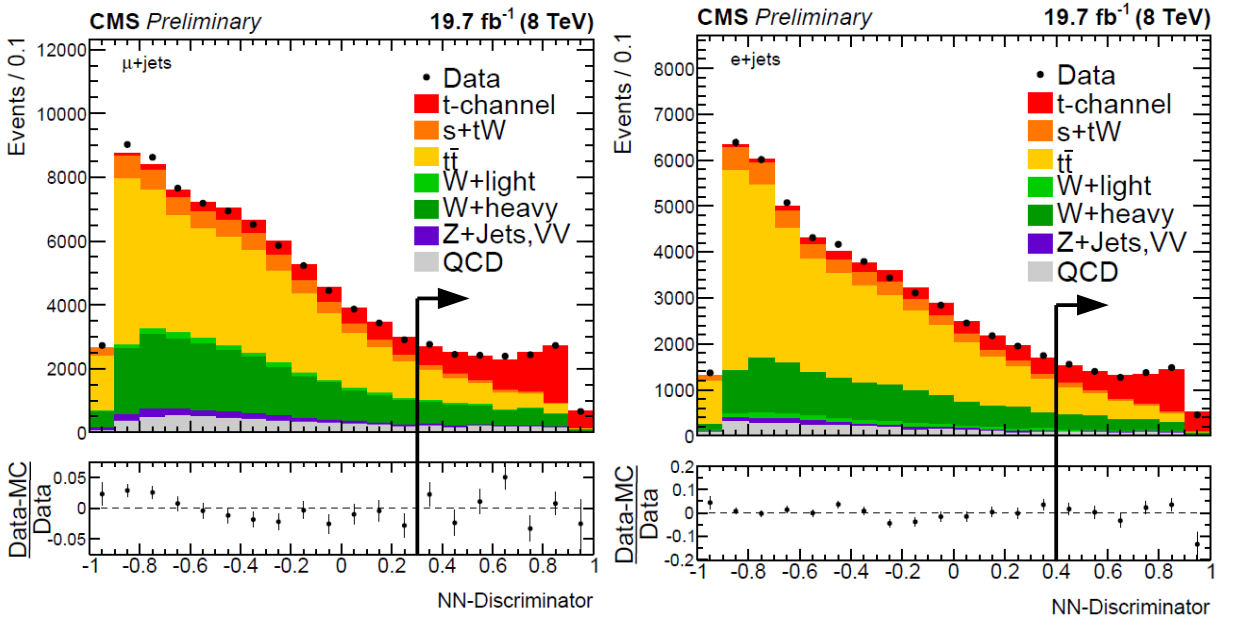
Object	Kinematic cuts at detector level	Cuts at particle level	number required
Tight Muon	$p_T > 26$, $\|\eta\| < 2.1$, $I_{rel} < 0.12$	$p_T > 30$, $\|\eta\| < 2.4$	exactly 1 (or 1 Ele)
Tight Electron	$E_T > 30$, $\|\eta\| < 2.4$, $I_{rel} < 0.1$	$p_T > 30$, $\|\eta\| < 2.4$	exactly 1 (or 1 Mu)
Veto 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)	$\not{E}_T > 45$	-	-

uncertainty on acceptance

Model	$\sigma^{fid}_{t\text{-ch}}$	scale	PDF
aMC@NLO 4FS, muons	1.646	$^{+0.029}_{-0.052}$	$^{+0.008}_{-0.009}$
aMC@NLO 4FS, electrons	1.640	$^{+0.027}_{-0.048}$	$^{+0.008}_{-0.009}$
POWHEG 4FS, muons	1.711	$^{+0.029}_{-0.052}$	$^{+0.009}_{-0.009}$
POWHEG 4FS, electrons	1.709	$^{+0.027}_{-0.048}$	$^{+0.009}_{-0.009}$
POWHEG 5FS, muons	1.762	$^{+0.006}_{-0.023}$	$^{+0.009}_{-0.009}$
POWHEG 5FS, electrons	1.755	$^{+0.011}_{-0.009}$	$^{+0.009}_{-0.009}$
aMC@NLO 4FS, muons + electrons	3.286	$^{+0.056}_{-0.100}$	$^{+0.017}_{-0.018}$
POWHEG 4FS, muons + electrons	3.420	$^{+0.056}_{-0.100}$	$^{+0.017}_{-0.018}$
POWHEG 5FS, muons + electrons	3.517	$^{+0.016}_{-0.031}$	$^{+0.018}_{-0.018}$

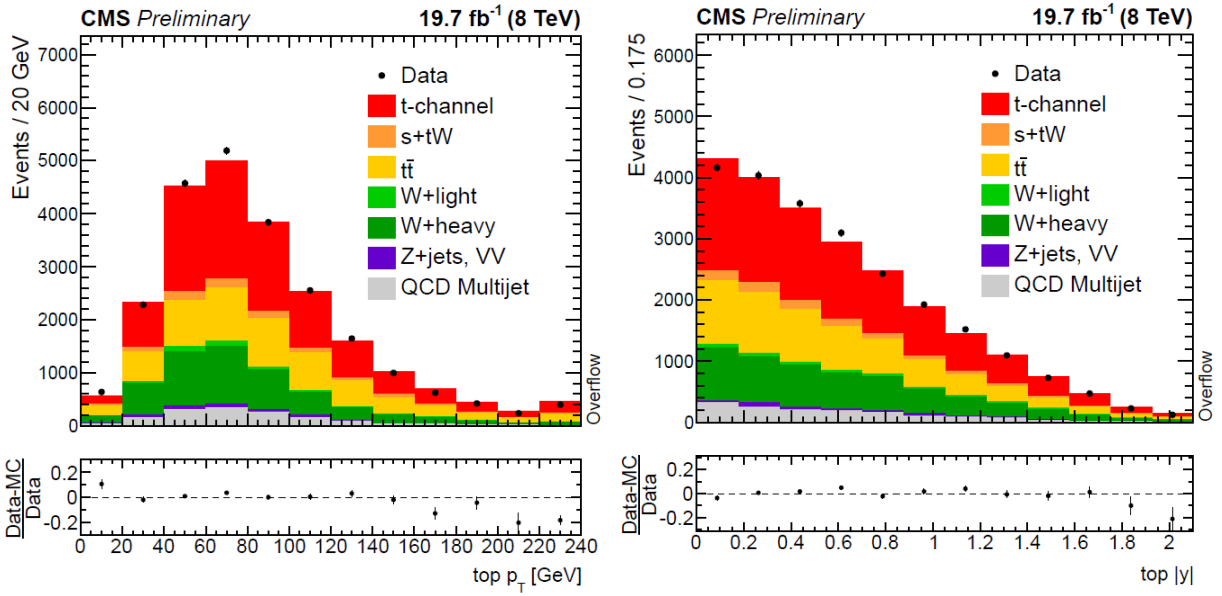
Differential t-channel @ 8 TeV

- neural network training



variable	rank in channel μ+jets	rank in channel e+jets	variable	rank in channel μ+jets	rank in channel e+jets
η_{lq}	1	1	C	11	12
$m_{\ell,\nu,b}$	2	2	$p_{T,lq}$	12	9
$m_{\text{jet1,jet2}}$	3	3	D	13	17
$m_{\text{T,W}}$	4	4	m_{jet1}	14	5
Q_ℓ	5	6	$E_{\text{T}}^{\text{miss}}$	15	14
m_{lq}	6	13	$\Delta\phi[jet2, \vec{\not{E}}_{\text{T}}]$	16	16
η_{W}	7	7	m_{jet2}	17	8
$\Delta\phi[\ell, lq]$	8	11	$\Delta R[jet1, \vec{\not{E}}_{\text{T}}]$	18	15
$m_{b_{top}}$	9	–	$\Delta\phi[jet2, \ell]$	–	10
$\Delta\phi[jet1, \vec{\not{E}}_{\text{T}}]$	10	–	$Aplanarity$	–	18

- resulting distributions in signal-enhanced phase space

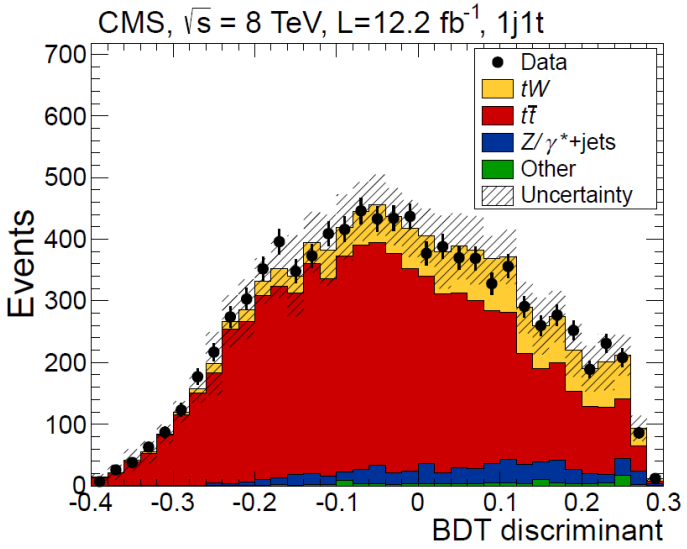


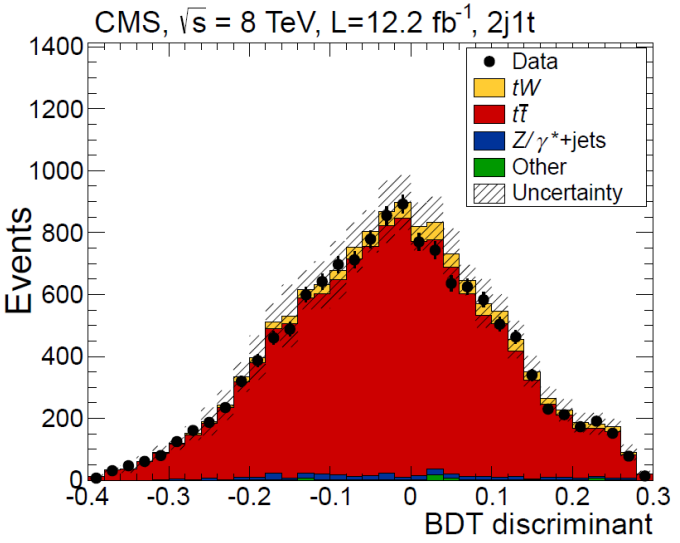
Top polarization uncertainties

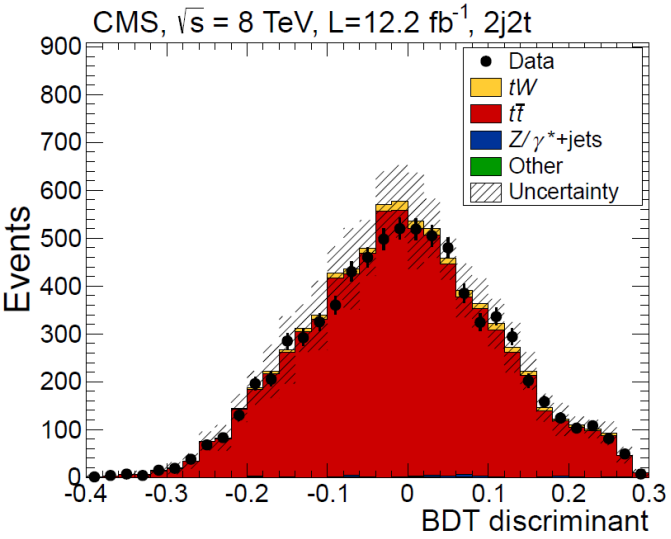
	$\delta A_\mu(\mathrm{t})/10^{-2}$	$\delta A_\mu(\bar{\mathrm{t}})/10^{-2}$	$\delta A_\mu(\mathrm{t}+\bar{\mathrm{t}})/10^{-2}$
Statistical	3.2	4.6	2.6
ML fit uncertainty	0.7	1.2	0.6
Diboson bkg. fraction	<0.1	<0.1	<0.1
Z/γ^*+jets bkg. fraction	<0.1	<0.1	<0.1
s-channel bkg. fraction	0.3	0.2	0.2
tW bkg. 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 $\not{E}_\mathrm{T}$	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
$\mathrm{t\bar{t}}$ renorm./fact. scales	2.2	3.4	2.7
$\mathrm{t\bar{t}}$ 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

tW plots

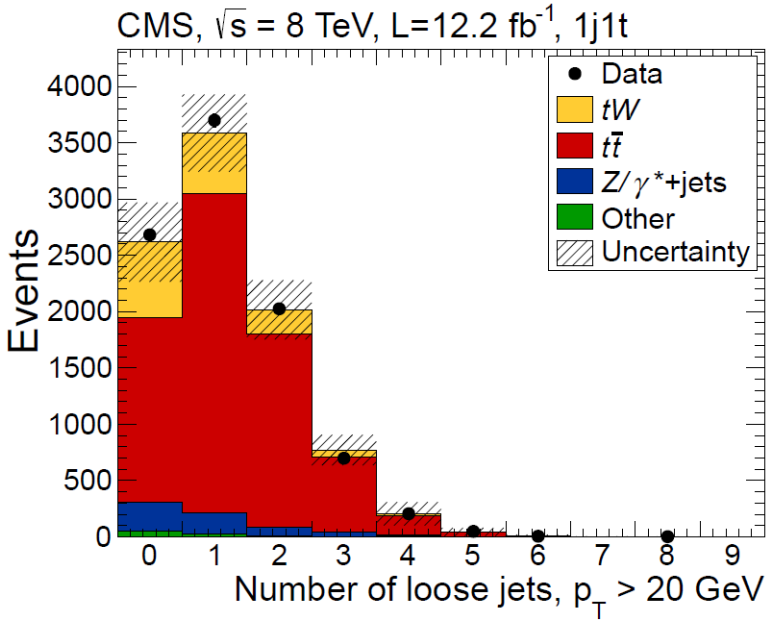
- BDT

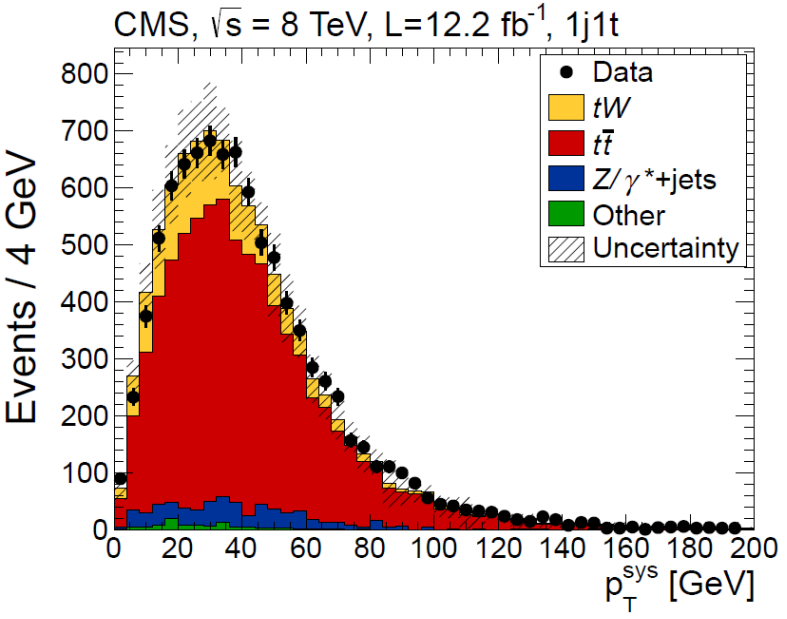






- few input variables





s-channel systematics

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

t-channel @ 13 TeV: Uncertainties

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

uncertainty source	$\Delta\sigma_{t-\text{ch.},t+\bar{t}}/\sigma^{\text{obs}}_{t-\text{ch.},t+\bar{t}}$	$\Delta\sigma_{t-\text{ch.},t}/\sigma^{\text{obs}}_{t-\text{ch.},t}$	$\Delta\sigma_{t-\text{ch.},\bar{t}}/\sigma^{\text{obs}}_{t-\text{ch.},\bar{t}}$
uncertainty of the fit (stat. + prof. unc.)	±6.8%	±7.4%	±11.9%
statistical uncertainty	±4.0%	±4.7%	±7.6%
profiled uncertainties	±5.5%	±5.7%	±9.2%
MC statistics	±2.8%	±3.4%	±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	±7.9%	±10.1%	±8.2%
$t\bar{t}$ modeling	±4.3%	±3.9%	±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	±0.1%	±0.1%	±0.2%
total theory uncertainties	-12.1/+12.6	-13.8/+13.6	-13.5/+13.4%
luminosity	±2.7%	±2.7%	±2.7%
total uncertainty	-14.5/+14.8%	-16.3/+16.1%	-18.6/+18.6%