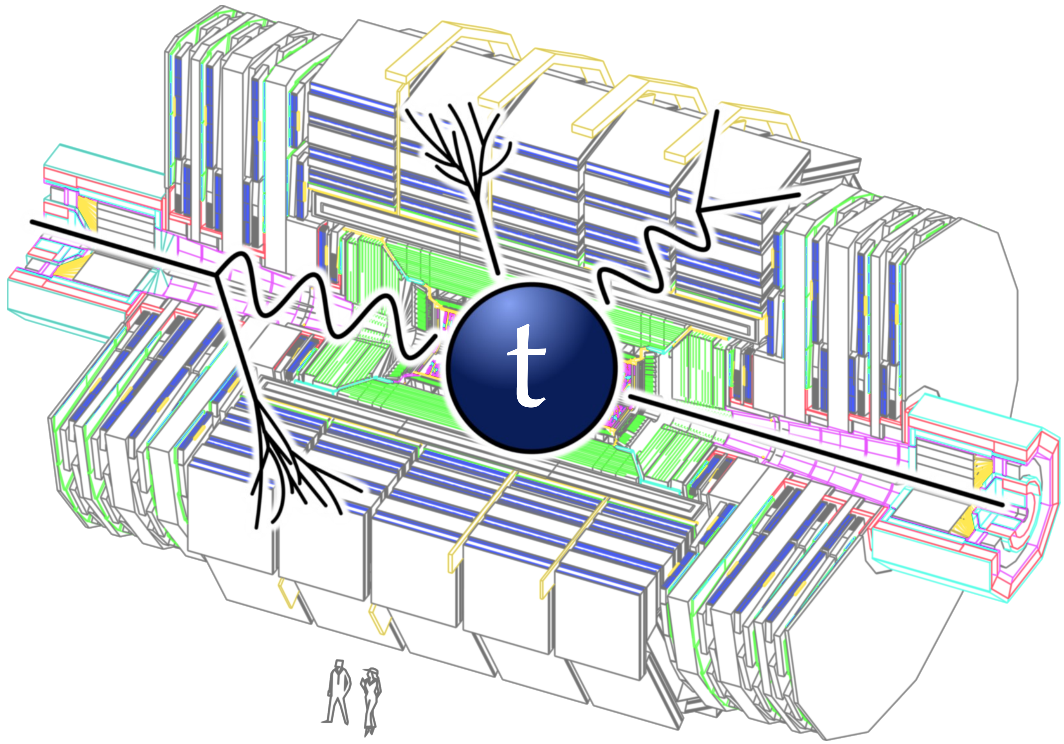


CMS single top update

TOP LHC WG Meeting

Matthias Komm

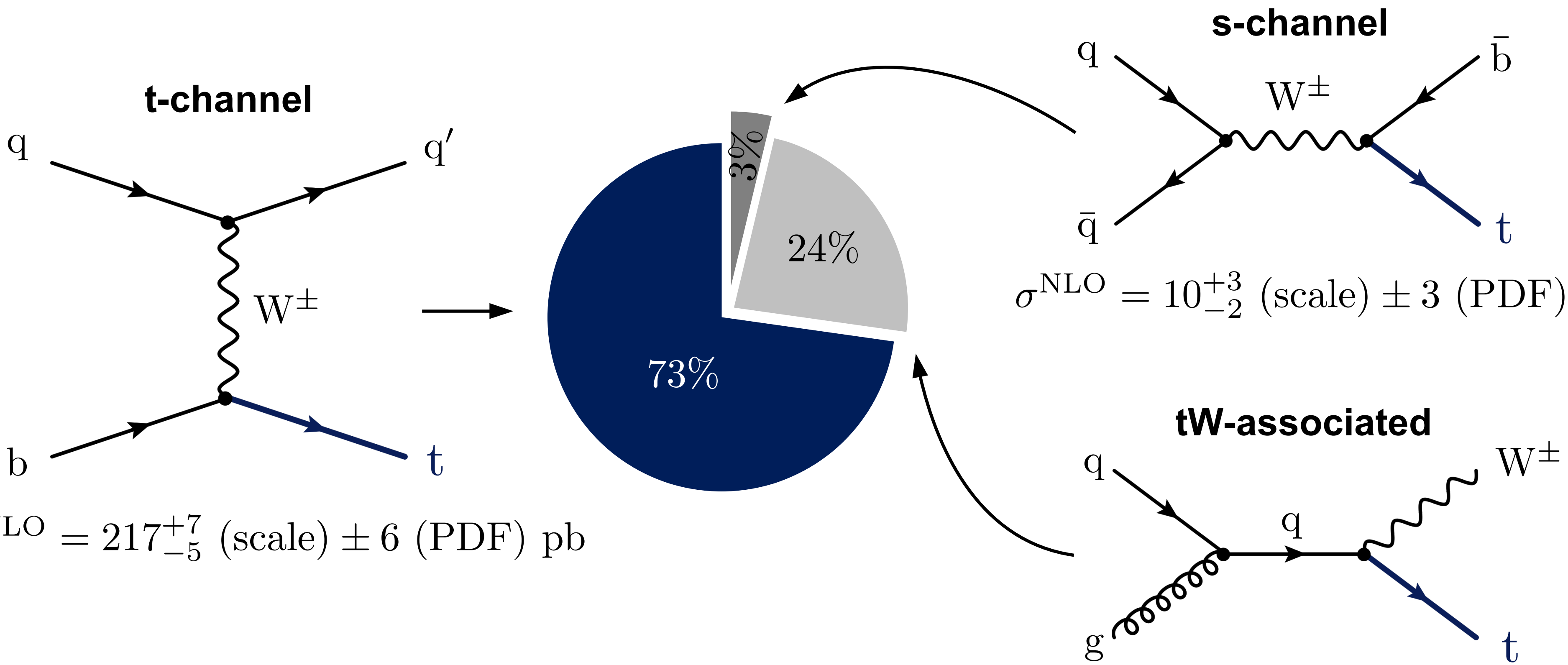
UCL Université catholique de Louvain

fnrs LA LIBERTÉ DE CHERCHER

Introduction

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SingleTopRefXsec
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, $m_{\mathrm{t}} = 172.5$)



$\sigma^{\mathrm{NLO}} = 217^{+7}_{-5}$ (scale) ± 6 (PDF) pb

$\sigma^{\mathrm{NLO}} = 10^{+3}_{-2}$ (scale) ± 3 (PDF) pb

$\sigma^{\mathrm{NLO+NNLL}} = 72 \pm 2$ (scale) ± 3 (PDF) pb

- 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)

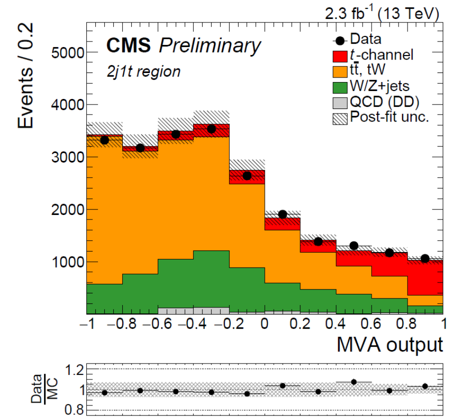
Outline

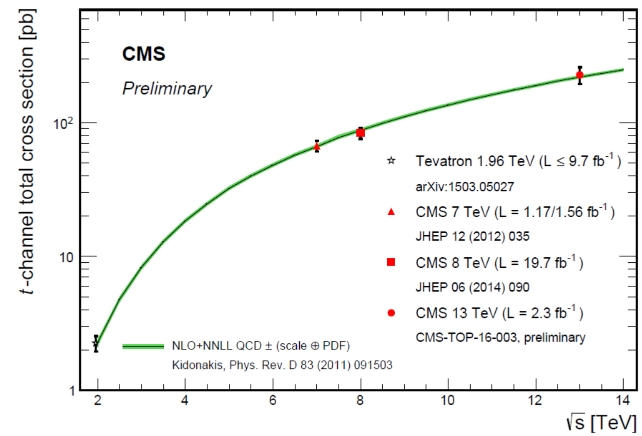
➢ measurement of ...

… inclusive t-channel single top quark production at 13 TeV

(CMS-PAS-TOP-16-003)

– event selection
– QCD estimation
– signal extraction using MVA
– statistical evaluation
– results

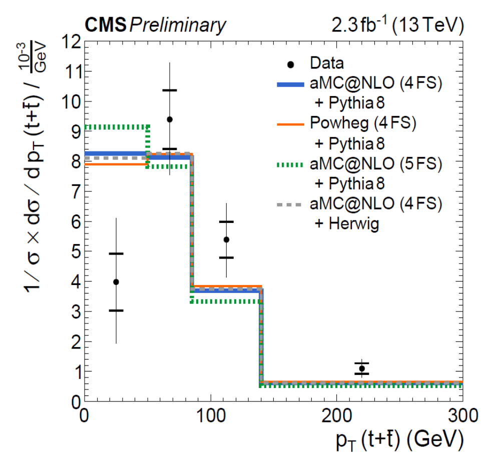


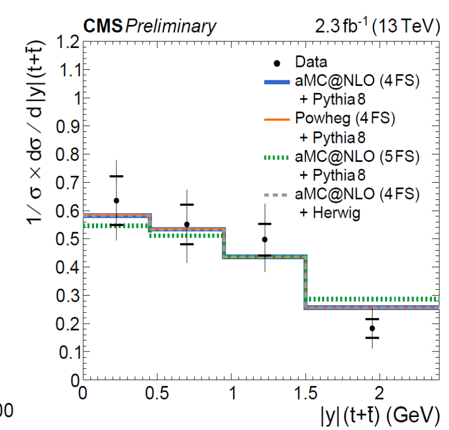


… differential t-channel single top quark production at 13 TeV

(CMS-PAS-TOP-16-004)

– single top reconstruction
– analysis strategy
– signal extraction
– unfolding
– results





Inclusive cross section measurement at 13 TeV

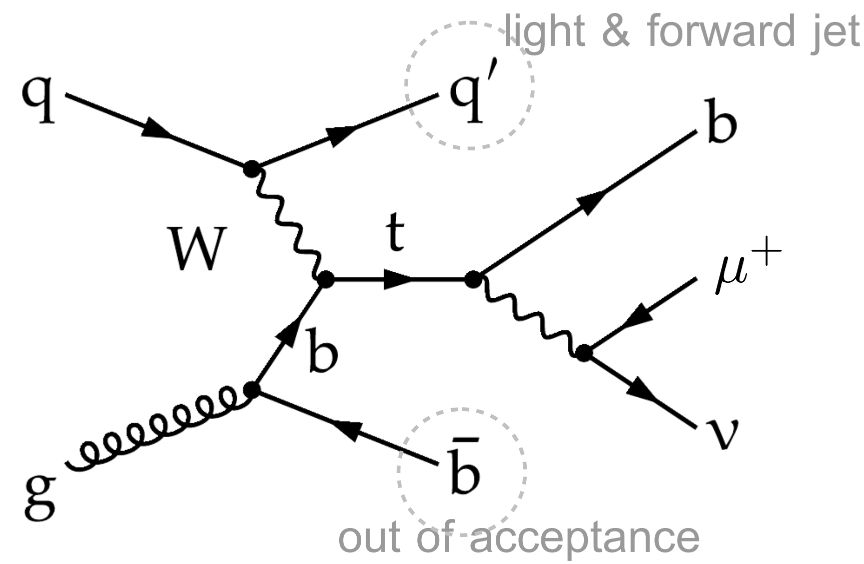
Event selection

- 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 $p_{\mathrm{T}} > 20\ \mathrm{GeV},\ |\eta| < 2.5$



- AK4 jets $p_{\mathrm{T}} > 40\ \mathrm{GeV},\ |\eta| < 4.7$

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

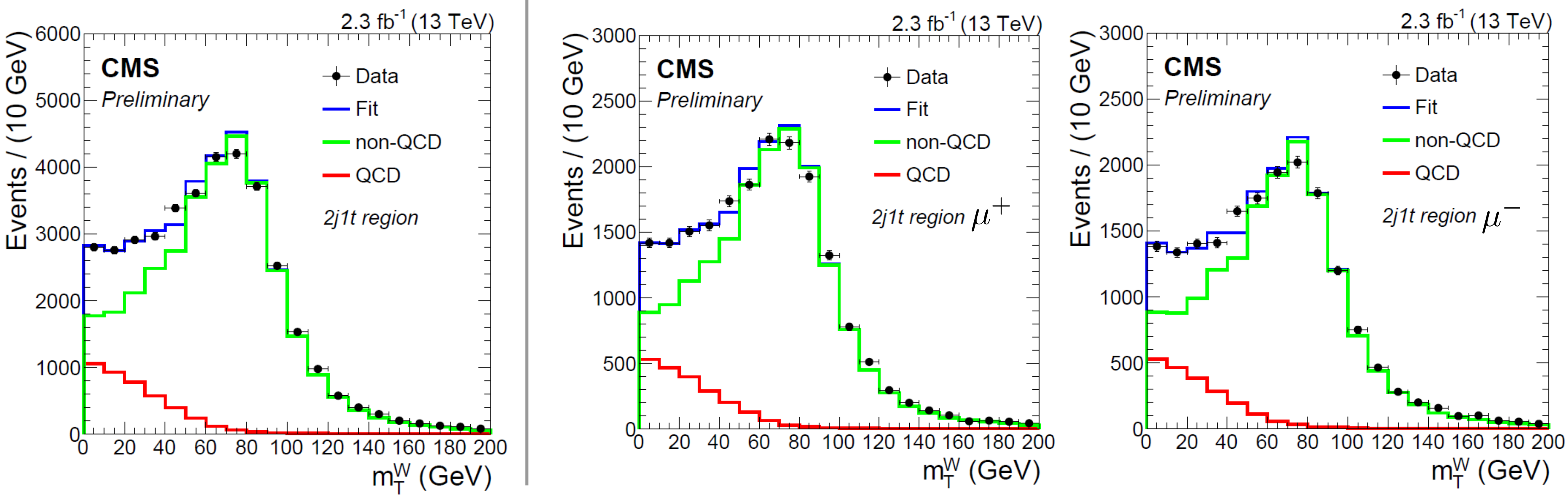
define signal & control regions
- 2 jets & 0 b-tags: W+jets
- 2 jets & 1 b-tag: signal
- 3 jets & 1, 2 b-tags: $t\bar{t}$

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

Signal extraction

- 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

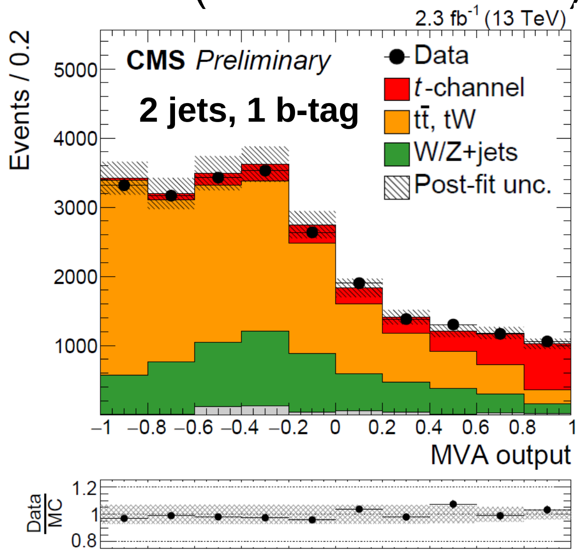


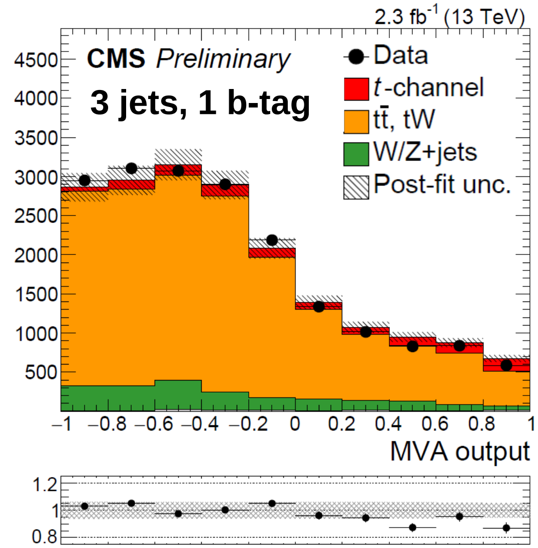
  - **signal & W+jet, $\mathrm{t\bar{t}}$ background** estimated using **neural network** discriminant
  - 11 input variables (ordered by decreasing importance):
    $|\eta(j')|$, reconstructed top quark mass, dijet mass, $m_{\mathrm{T}}(\mathrm{W})$, $\sum p_{\mathrm{T}}^{\mathrm{jet}}$,
    top quark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

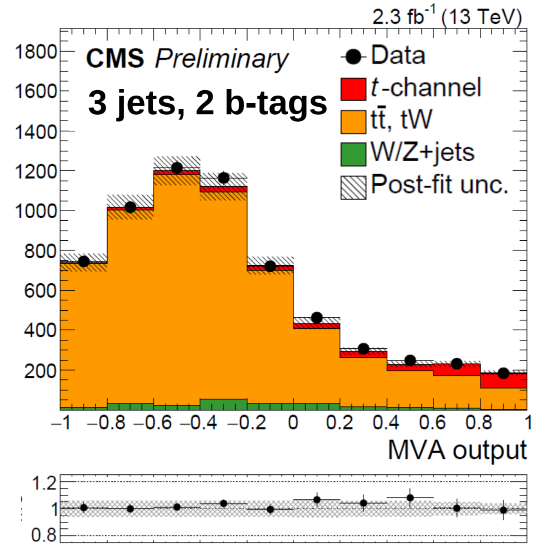
Signal extraction (2)

- 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

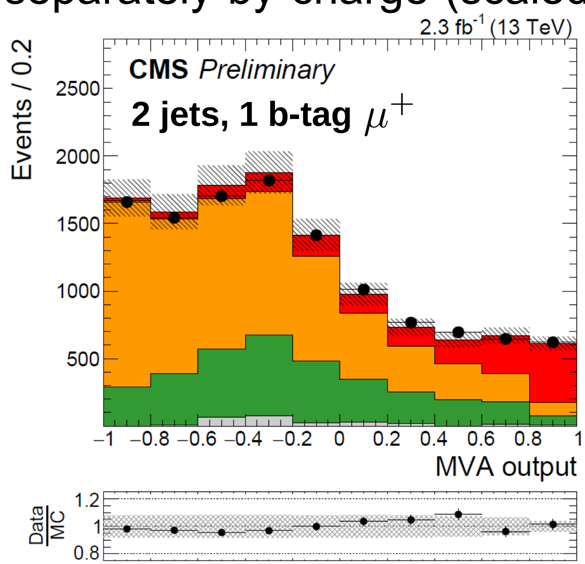
- inclusive (scaled to fit result)

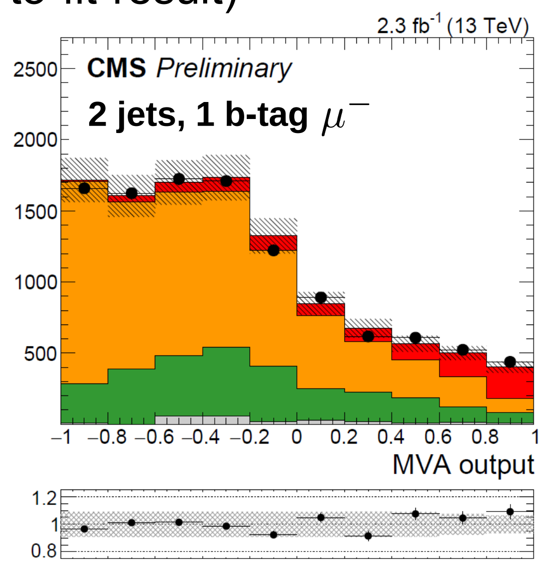






- separately by charge (scaled to fit result)





→ good agreement between data/MC

Statistical evaluation

- 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

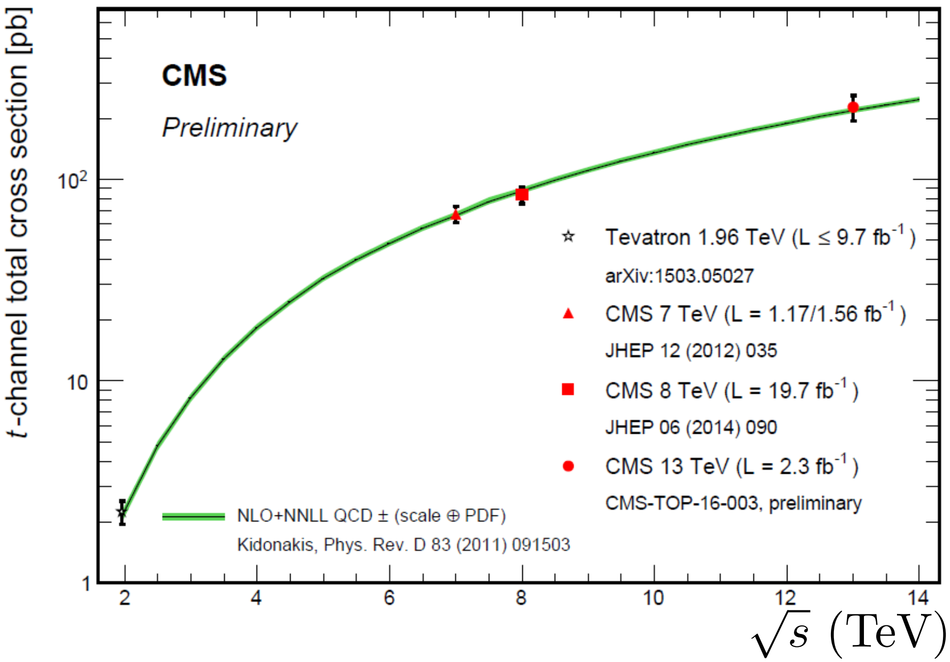
- result

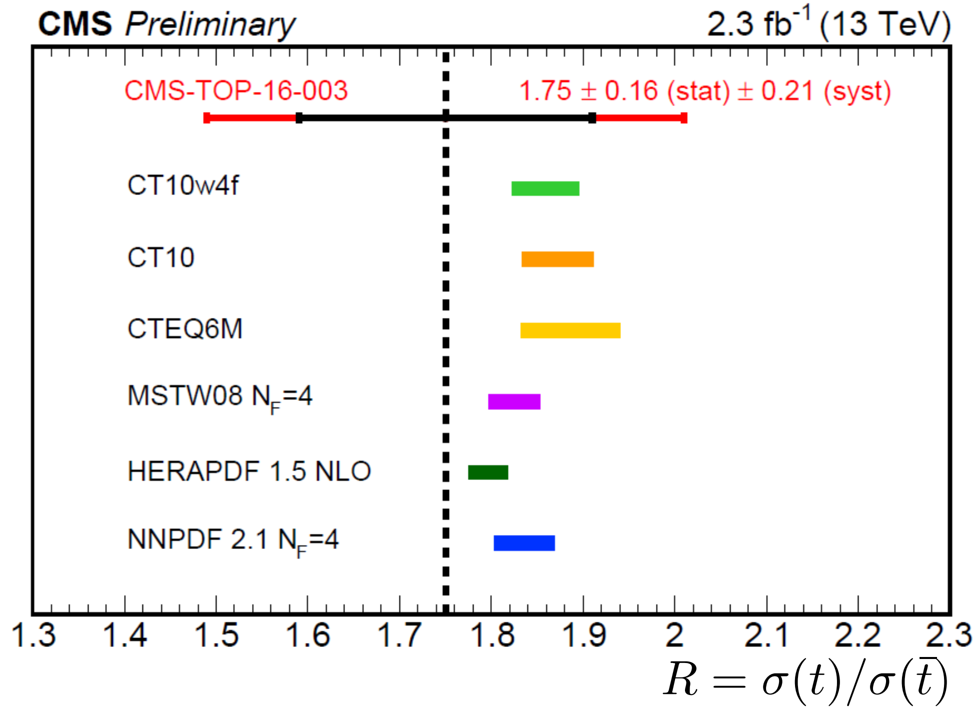
uncertainty source	$\Delta\sigma_{t-\text{ch.},t+\bar{t}}/\sigma^{\text{obs}}_{t-\text{ch.},t+\bar{t}}$	$\Delta\sigma_{t-\text{ch.},t}/\sigma^{\text{obs}}_{t-\text{ch.},t}$	$\Delta\sigma_{t-\text{ch.},\bar{t}}/\sigma^{\text{obs}}_{t-\text{ch.},\bar{t}}$
statistical uncertainty	±4.0%	±4.7%	±7.6%
profiled 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)

Result





- measured cross sections

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

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

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

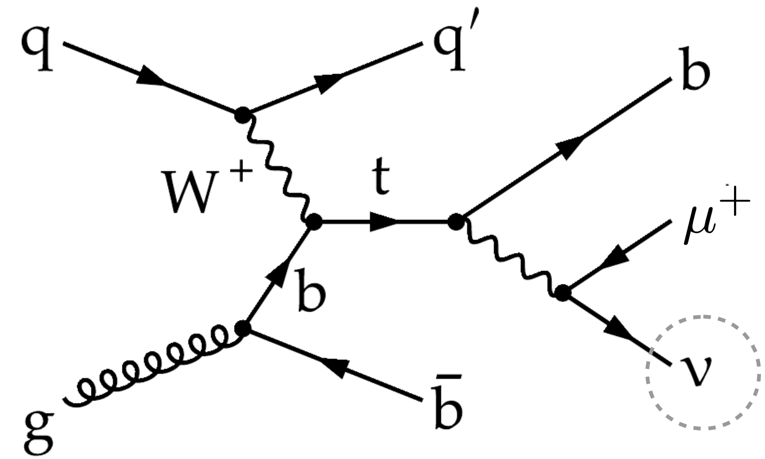
$$= 228 \pm 15\%\ \text{pb} \qquad \left[\sigma^{\text{SM}} = 217^{+9}_{-8}\ \text{pb}\right]$$

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

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

Differential cross section as function of $p_{\mathrm{T}}^{\mathrm{top}}$ & $|y^{\mathrm{top}}|$ at 13 TeV

Analysis strategy



- event selection
  → (nearly) identical to inclusive cross section measurement

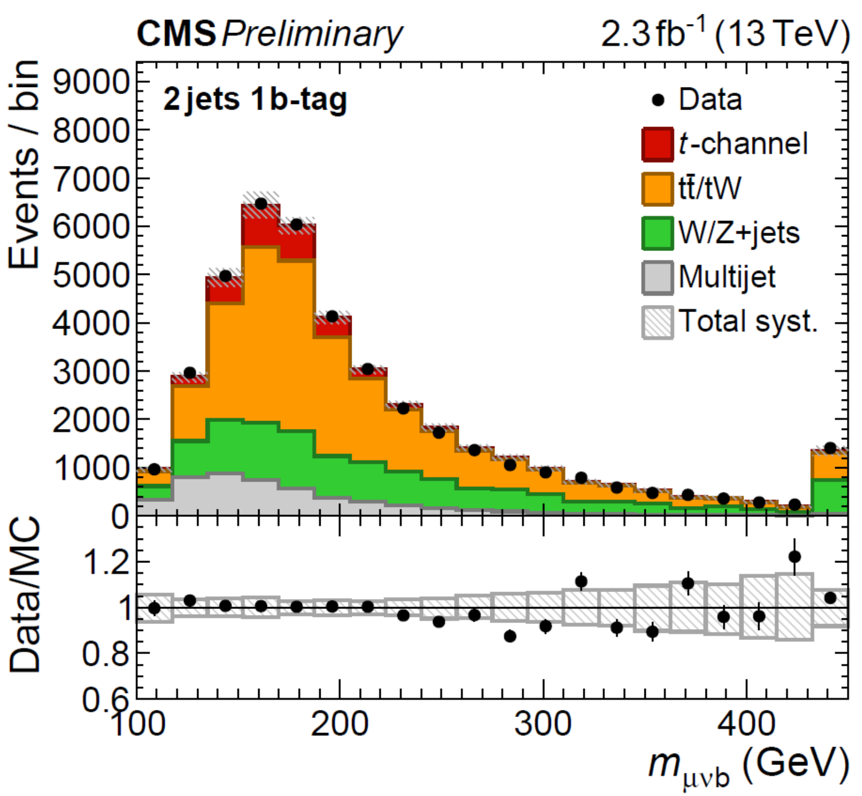
- top quark reconstruction
  solve p_z^ν-component using W boson mass constraint

$$m_{\mathrm{W}}^2 = \begin{pmatrix} E_{\mathrm{W}} \\ \vec{p}_{\mathrm{W}} \end{pmatrix}^2 = \left[\begin{pmatrix} E_\mu \\ \vec{p}_\mu \end{pmatrix} + \begin{pmatrix} E_\nu \\ \vec{p}_\nu \end{pmatrix} \right]^2$$

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

$$a = \frac{m_{\mathrm{W}}^2}{2} + \not{E}_{\mathrm{T}} p_{\mathrm{T}}^\mu \cdot \cos(\phi_\mu - \phi_\nu)$$

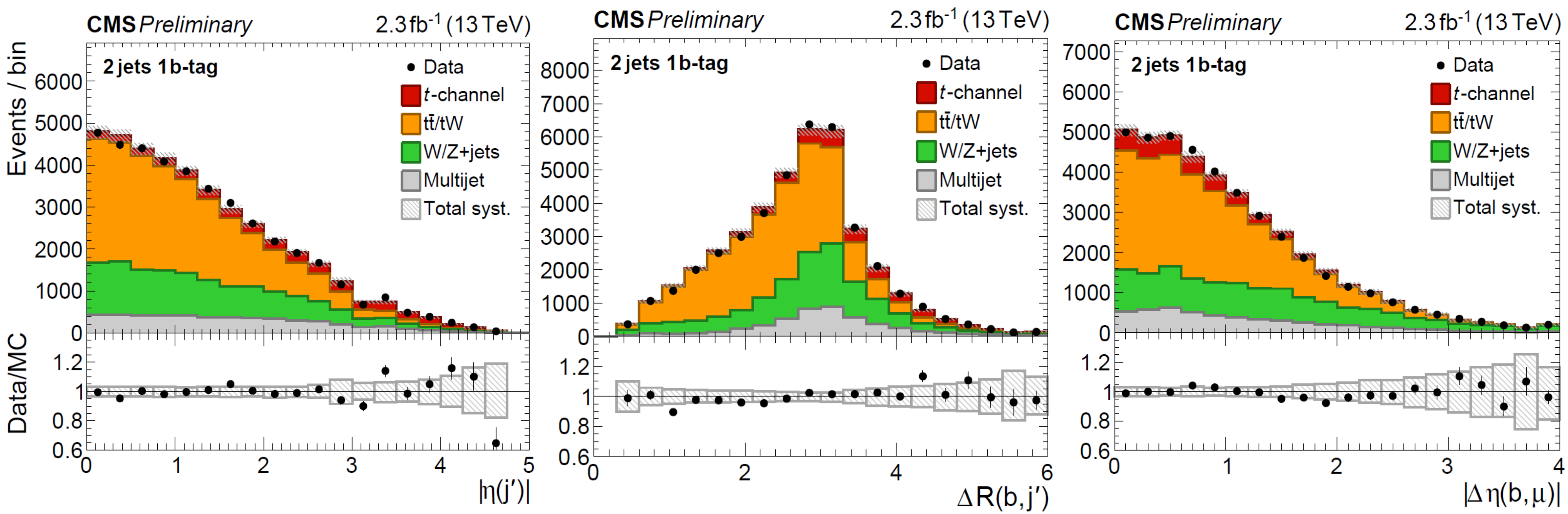
- 2 cases
  - 2 real solutions ($\frac{2}{3}$ of signal events)
    → pick smaller $|p_z^\nu|$ solution
  - complex solutions
    → set $\sqrt{a^2 - \not{E}_{\mathrm{T}}^2 (E_\mu^2 - p_{\mu,z}^2)} = 0$
    → modify $p_{x,y}^\nu$



Analysis strategy (2)

- 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

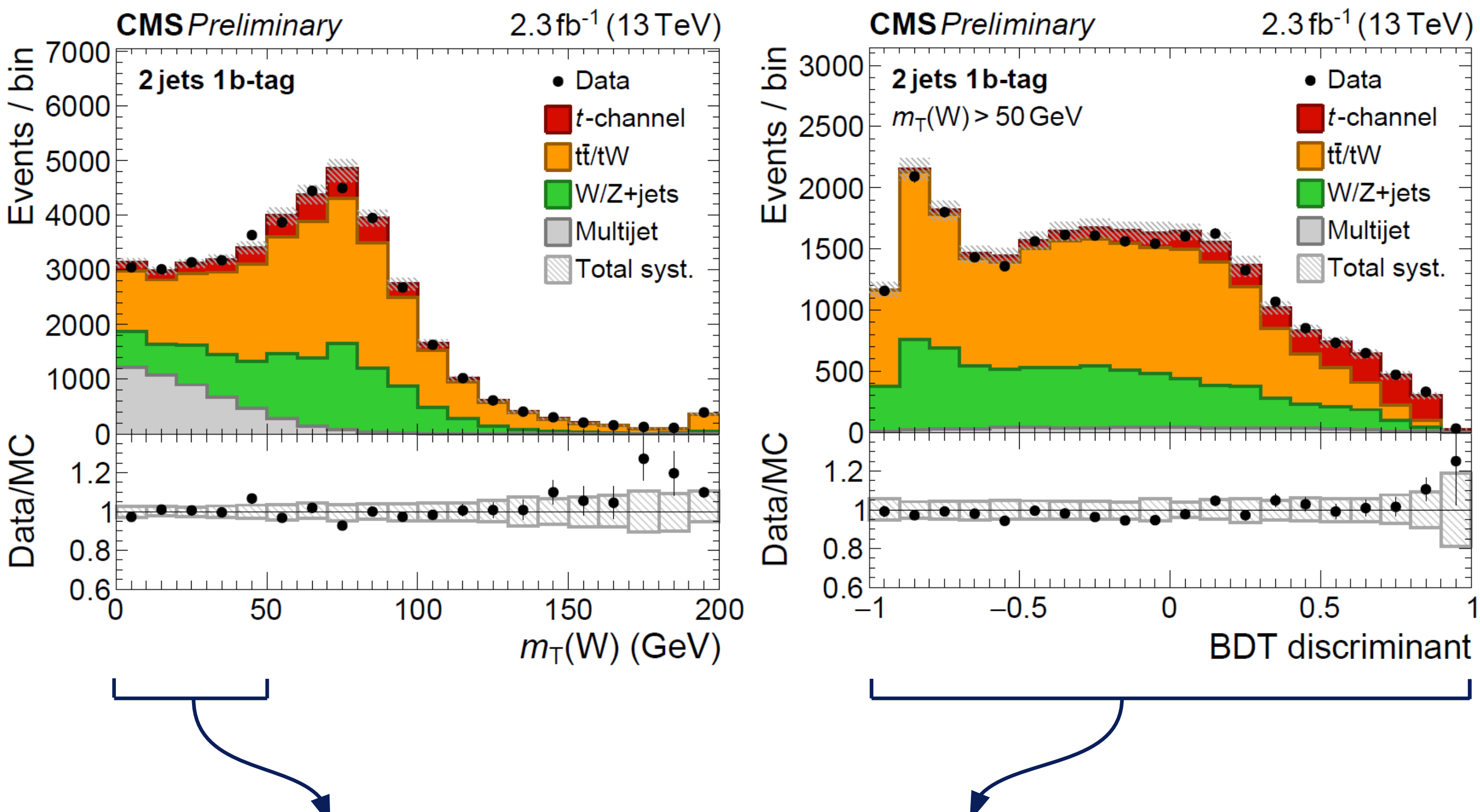
- train BDT to separate signal from W+jets, $t\bar{t}$ & QCD background
  - 5 input variables (uncorrelated to top quark p_{T}, $|y|$)
    $|\eta(j')|$, reconstructed top quark mass, $m_{\mathrm{T}}(\mathrm{W})$, $\Delta R(b,j')$, $|\Delta\eta(b,\mu)|$



→ data well modeled by simulation

Signal extraction

- 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)

Unfolding

- TUnfold package
  unfolding as minimization

$$\chi^2 = (\vec{y} - \mathcal{A}\vec{x})^T \mathcal{V}_{yy}^{-1} (\vec{y} - \mathcal{A}\vec{x}) + \underbrace{\mathfrak{R}_1 + \mathfrak{R}_2}_{\text{penalty terms}}$$

$\mathfrak{R}_1 = \tau^2 \vec{x}^T \mathcal{L}^T \mathcal{L} \vec{x}$ → suppresses oscillations (regularization)

$\mathfrak{R}_2 = \lambda\left(\sum y_i - \vec{\epsilon} \cdot \vec{x}\right)$ → matches selection efficiency

- setup
  - regularization strength set to minimal global correlation
  - choice of binning
    - require high purity & stability (>50%)
    - less curvature of expectation (minimizes regularization bias)
  - input: signal MC scaled to fit results (no selection on BDT discriminant)

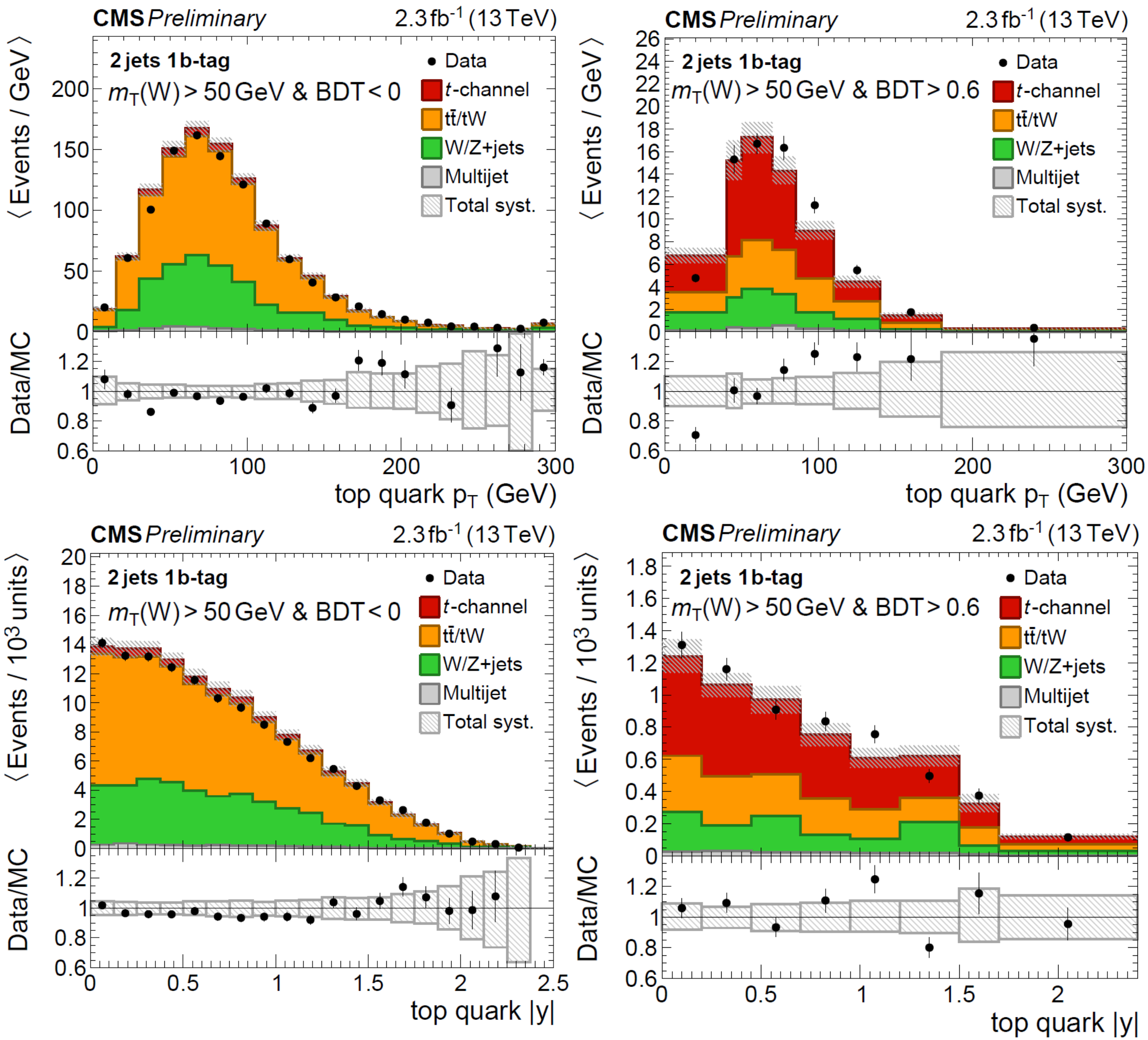
purity
$$P_i = \frac{\mathcal{A}_{ij}}{\sum_j^{\text{reco.}} \mathcal{A}_{ij}}$$

stability
$$S_j = \frac{\mathcal{A}_{ij}}{\sum_i^{\text{gen.}} \mathcal{A}_{ij}}$$

- parton level top quark definition
  - on-shell top quark after QCD & QED radiation including intrinsic k_{T} of initial partons
  - technical: “last copy of particle instance” or Pythia8 status 62

Unfolding (2)

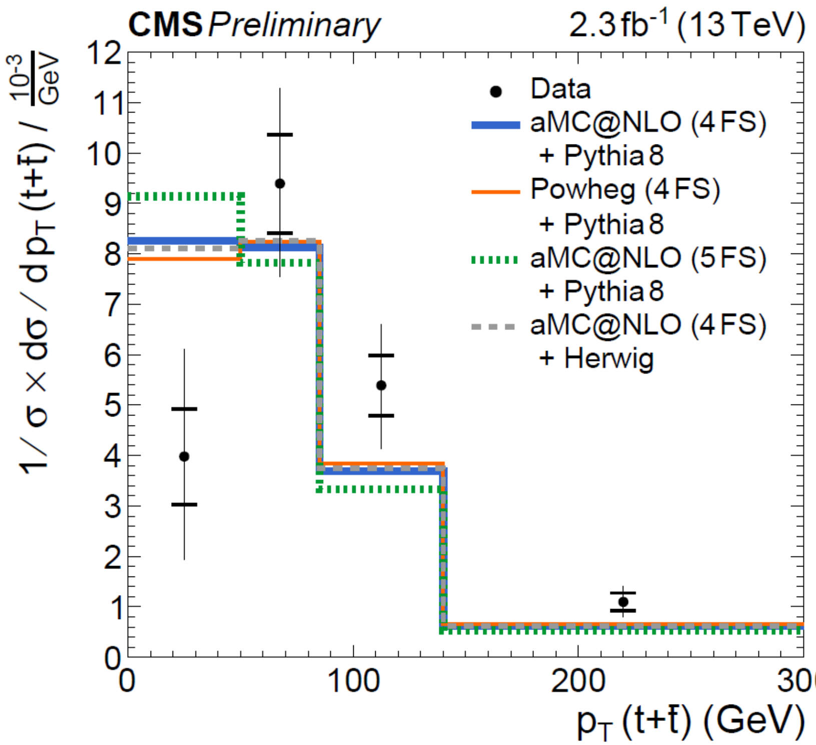
- modeling in signal-depleted & signal-enhanced regions using additional BDT selection

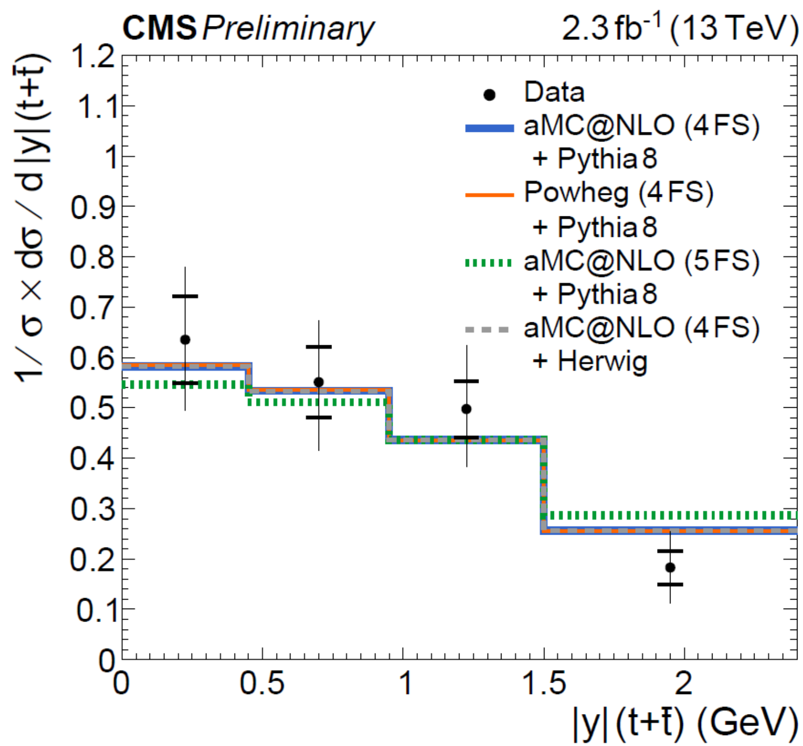


- signal-depleted region well modeled by simulation
- data display slightly harder p_T spectrum than simulation for signal
- rapidity well described in both regions

Result

- 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%)

Conclusion

- measurement of…

  … inclusive t-channel single top quark production at 13 TeV

  (CMS-PAS-TOP-16-003)

  - event selection
  - signal extraction
  - systematic uncertainties

  most precise result to date at 13 TeV

  $$\sigma(t+\bar{t})_{\mathrm{CMS}} = 228 \pm 15\%\ \mathrm{pb}$$

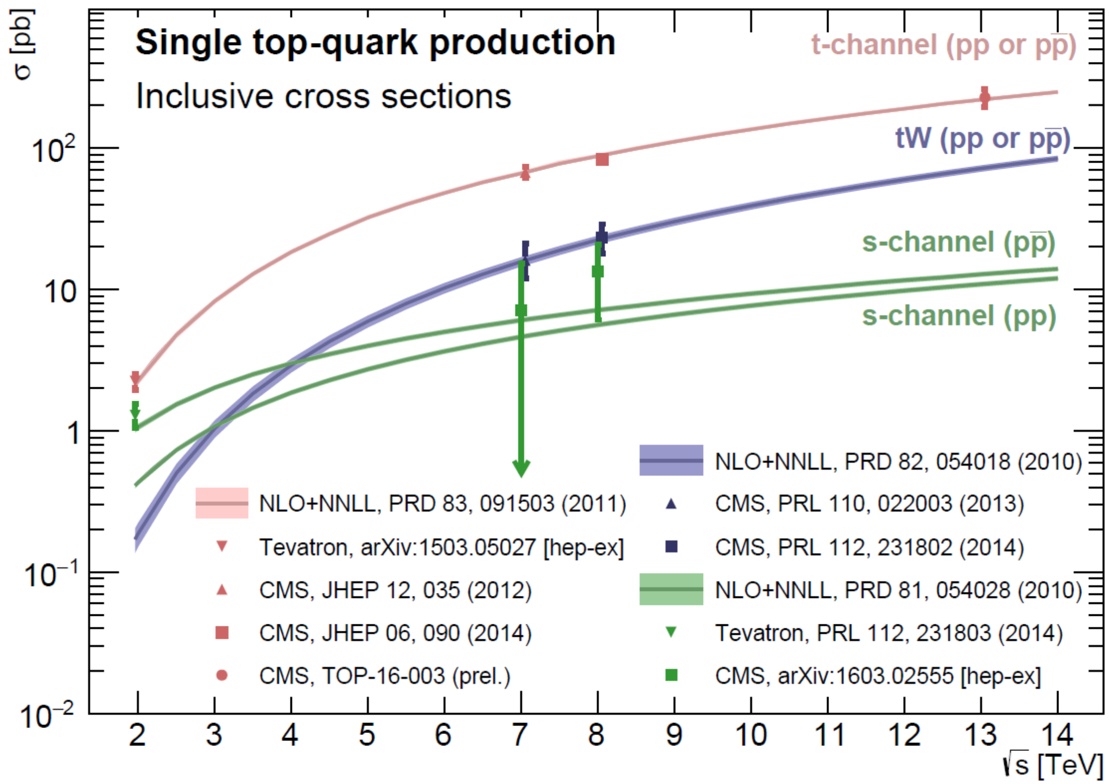
  $$\sigma(t+\bar{t})_{\mathrm{ATLAS}} = 229 \pm 21\%\ \mathrm{pb}$$

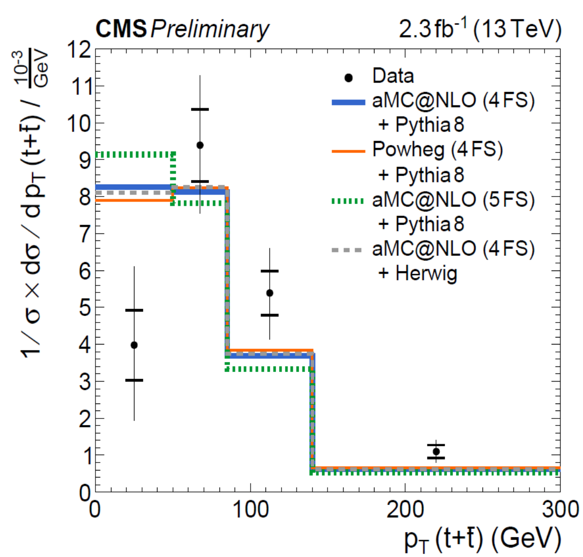
  (ATLAS-CONF-2015-079)

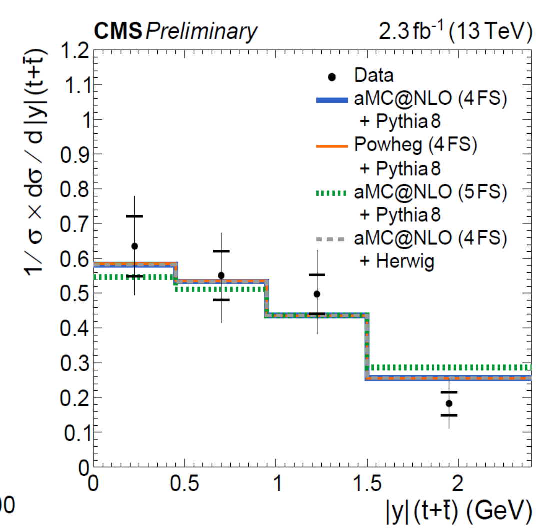
  … differential t-channel single top quark production at 13 TeV

  (CMS-PAS-TOP-16-004)

  - top quark reconstruction
  - anlysis strategy
  - unfolding







Backup

Systematic 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%